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THE POTENTIAL FOR ELECTRICITY EFFICIENCY IMPROVEMENTS IN THE U.S. RESIDENTIAL SECTOR

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EXECUTIVE SUMMARY

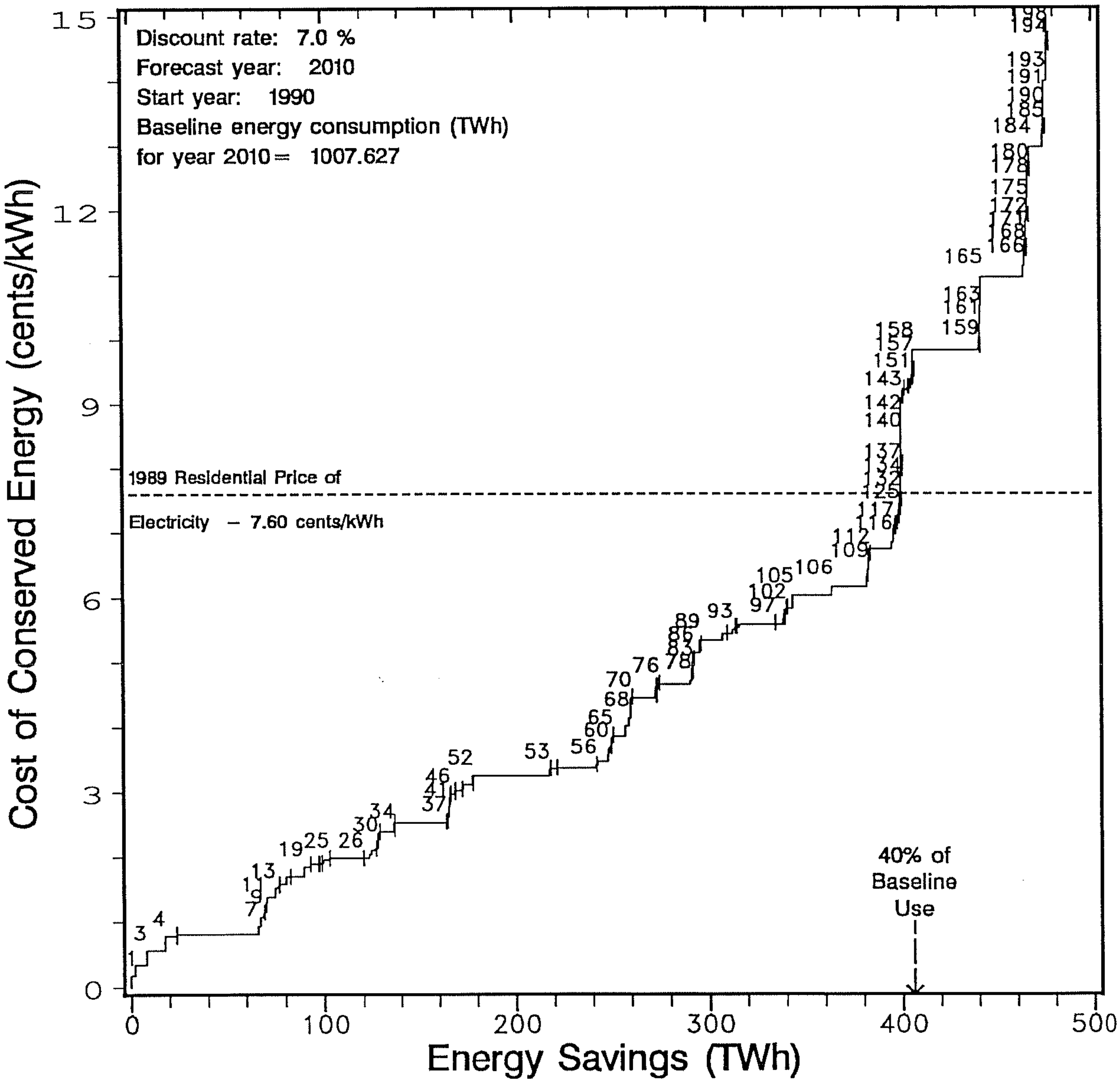
This report describes and documents an ongoing analysis of the technical potential for electricity efficiency improvements in the U.S. residential sector. Previous analyses have estimated the conservation potential for other countries, states, or individual utility service territories. As concern over greenhouse gas emissions has increased, interest has grown in estimates of conservation potential for the U.S. residential sector as a whole. Earlier estimates of U.S. conservation potential are either out of date or are less detailed than is desirable for engineering-economic estimates of the costs of reducing carbon emissions.

This study represents the most elaborate assessment to date of U.S. residential sector electricity efficiency improvements. It relies on regional disaggregation of input data, a state-of-the-art database of appliance efficiency and costs developed for the U.S. Department of Energy, and detailed analysis of thermal integrity measures in single-family dwellings. Fuel switching from electricity to direct use of natural gas has been included for water heaters, ranges, and clothes dryers. Advanced technologies (including "superwindows", spectrally-selective glazings, evacuated panels for refrigerators, and heat-pump water heaters) have been included based on engineering estimates of their costs and dates of availability.

Some promising efficiency technologies have been omitted because we lacked data, including thermal integrity improvements for new and existing multifamily buildings and mobile homes, integrated appliances, and advanced insulation technologies for new single-family homes. This study also does not include load management technologies (which may improve the overall efficiency of the electric utility system) or electrotechnologies that may increase the use of electricity but reduce primary energy consumption.

Efficiency improvements have been characterized in terms of their cost of conserved energy ($/kWh), for convenient comparison with the cost of competing electricity generating technologies. Figure ES-1 summarizes the results of this cost analysis. The total technical potential (without considering cost) is about 486 TWh, or about 48% of the frozen efficiency baseline. Total technical potential savings costing less than 7.6¢/kWh are 404 TWh/year by 2010, at an average cost of 3.4 ¢/kWh. If fully captured, savings costing less than 7.6¢/kWh would correspond to the output of 70-75 baseload (1000 MW) coal or nuclear plants.

Figure ES–1: Maximum Technical Potential in 2010

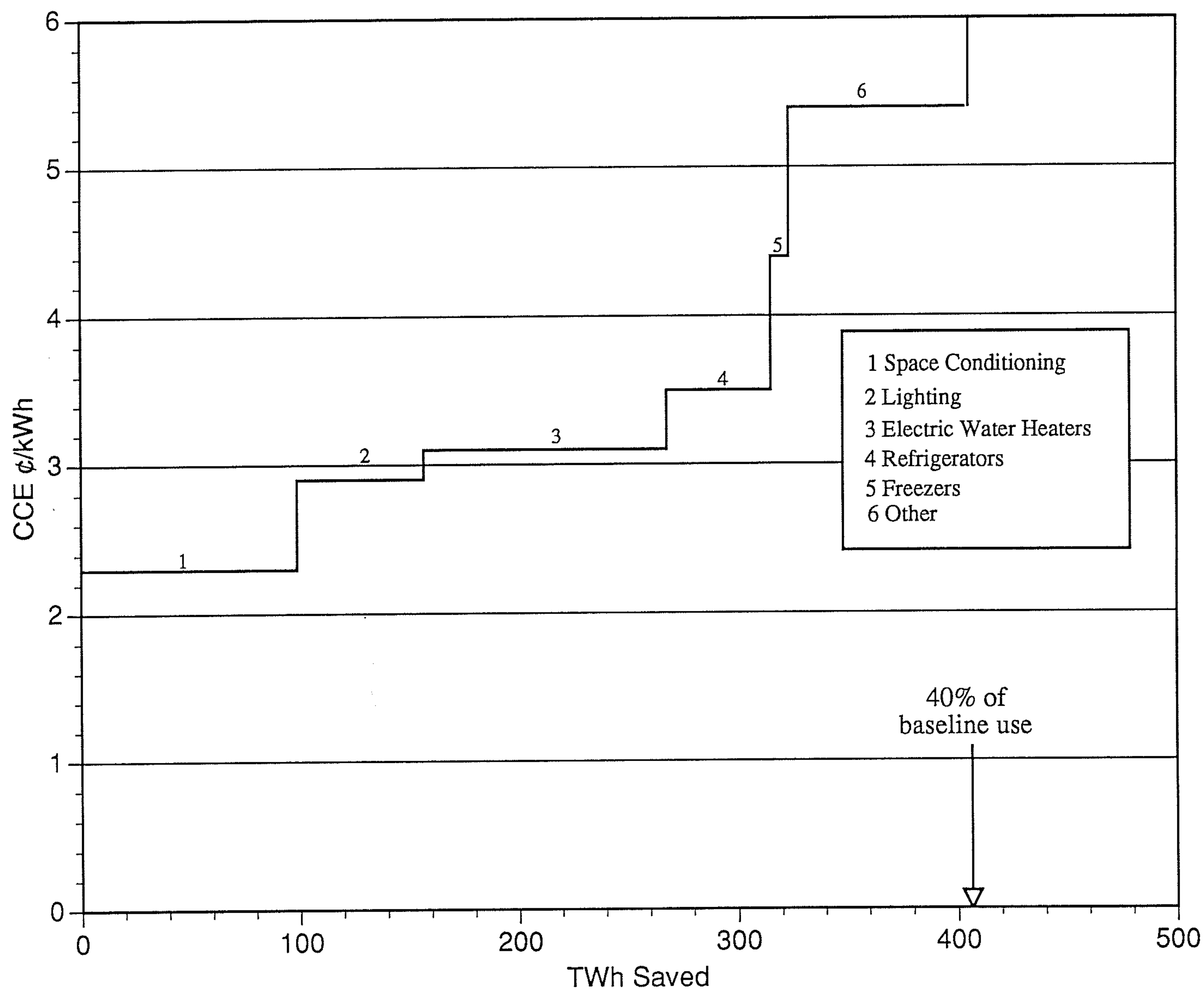


A supply curve of conserved electricity for the United States residential sector. Each step represents a conservation measure (or a package of measures). The width of the step indicates the nationwide electricity savings from the measure and the height of the measure indicates the cost of conserved electricity. The end uses include space conditioning, water heating, refrigeration, lighting, and miscellaneous.

Figure ES-2 shows that electric water heating measures offer the largest potential savings (in absolute terms) for costs less than 7.6¢/kWh of any single end use (slightly more than 110 TWh, of which about 17 TWh, or roughly 15%, is attributable to fuel switching to natural gas). Savings from space conditioning are next most important in absolute terms, totalling about 100 TWh. Lighting measures save about 60 TWh, as do refrigerator and freezer measures together. In percentage terms (relative to each end-use category's baseline usage), water heating savings potential is the greatest (60%), followed by lighting (47%), refrigerators (39%), and space conditioning (31%).

Some of the technologies identified in this study will be adopted as the result of market forces, hence some of the efficiency improvements embodied in these technologies are reflected (either explicitly or implicitly) in government agencies' and utilities' business-as-usual projections of electricity demand. Nonetheless, our analysis shows that a significant potential exists to reduce residential electricity demand compared to projected demand in 2010.

Figure ES-2: Energy Savings and Costs by End-Use in 2010



Each segment of this curve shows the total electricity savings and the average cost of conserved energy for all measures in Figure ES-1 that cost less than 7.6¢/kWh (grouped by end use).

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I. INTRODUCTION

This study represents the most elaborate assessment to date of U.S. residential sector electricity efficiency improvements. Previous analyses (Bodlund et al. 1989, Geller et al. 1986, Hunn et al. 1986, Krause et al. 1987, Lovins 1987, Meier et al. 1983, Miller et al. 1989, NEEPC 1987, NPPC 1986, NPPC 1989, Usibelli et al. 1983, XENERGY 1990) have estimated the conservation potential for other countries, states, or individual utility service territories. As concern over greenhouse gas emissions has increased, interest has grown in estimates of conservation potential for the U.S. residential sector as a whole. The earliest detailed estimate of U.S. conservation potential is now out of date (SERI 1981), while more recent estimates (Carlsmith et al. 1990, EPRI 1990) are less detailed than is desirable for engineering-economic estimates of the costs of reducing carbon emissions.

In this paper, we first describe the methodology for creating supply curves of conserved energy, and then illustrate the subtleties of assessing the technical conservation potential. Next, we present the data and forecasts used in this assessment, including costs, baseline thermal characteristics, energy use, and energy savings. Finally, we present the main results and conclusions from the analysis, and discuss future work.

II. METHODOLOGY

The two essential elements of an analysis of future conservation potential are: 1) a database of measures for improving energy efficiency, including costs and energy savings for each measure, and 2) a detailed baseline forecast of typical future technologies that will be installed in the absence of policy action, including the number of devices, their cost, and their expected energy consumption. A supply curve analysis involves "implementing" the conservation options and calculating how that implementation would change the energy use in the baseline forecast.

Section II.A describes in general terms the concept of conservation supply curves. Section II.B presents the definitions and general assumptions used in this analysis. Section II.C describes the baseline frozen efficiency forecast, and Section II.D discusses the database of conservation measures.

A. Supply curves of conserved energy

Previous analyses have developed and used the concept of *supply curves of conserved energy* for assessing conservation potentials (Bodlund et al. 1989, Geller et al. 1986, Hunn et al. 1986, Krause et al. 1987, Lovins 1987, Meier et al. 1983, Miller et al. 1989, NEEPC 1987, NPPC 1986, NPPC 1989, Usibelli et al. 1983, XENERGY 1990) A supply curve of conserved energy is a graph that shows the amount of energy saved (TWh) on the x-axis and the cost of conserved energy or CCE (¢/kWh) on the y-axis.[1]

CCE is calculated using Equation (1):

$$\text{CCE (¢/kWh)} = \frac{\text{Capital Cost x } \dfrac{d}{(1-(1+d)^{-n})}}{\text{Annual Energy Savings}} \qquad (1)$$

[1]For more details see Meier et al. (1983).

where d is the discount rate (7%) and n is the lifetime of the conservation measure. The numerator in the right hand side of Equation 1 is the annualized cost of the conservation investment. Dividing annualized cost by annual energy savings yields the CCE, which can be compared to the busbar cost of a power plant.

Method of ranking conservation measures

To create the supply curve, conservation measures are ranked in order of increasing CCE. Determining this order is simple for efficiency measures that are independent. However, the ranking becomes complex when the energy saved by one conservation measure depends on the efficiency measures that have been implemented previously. For example, a typical supply curve might include conservation measures applied to a residential water heating system. The energy savings attributed to an improvement in the water heater's efficiency will depend on the amount of hot water demanded, which, in turn, will depend on the measures that have already been implemented (such as low-flow showerheads). Put another way, the sum of savings of each measure implemented alone will be greater than the two implemented together. If the interdependence of the measures is not taken into account, it is possible to "double-count" the energy savings.

A properly-constructed supply curve of conserved energy will avoid double-counting errors by using the following procedure:

(1) The CCE is calculated for all of the measures.

2) The cheapest (i.e., lowest CCE) measure is selected and "implemented", that is, the energy savings from the first measure are subtracted from the initial energy use.

3) The new energy use is used to recalculate the CCEs of the remaining measures. (In general, their CCEs will rise.)

4) The measure with the next lowest CCE is selected, and implemented.

5) The energy savings of the remaining measures are recalculated, and the measures are re-ranked.

This procedure is repeated until all the measures have been ranked (Meier 1982). For this project, the determination of the optimal sequence is performed exogenously, before the measures are entered in the supply curve program.[2]

Cost effectiveness

The CCE is, in most cases, independent of electricity price[3], and hence cannot by itself indicate whether a conservation measure is cost effective. By cost effective, we mean that the cost of investing in conservation is lower than the costs avoided by this investment. The assessment of cost effectiveness cannot be undertaken without specifying the perspective of

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[2] We call this program ACCESS (this name is not an acronym).

[3]our characterization of fuel switching from electricity to direct use of natural gas includes the present valued cost of gas in the CCE (see below). This convention makes the CCE for fuel switching consistent with the CCEs for efficiency improvements, but it makes the CCE for fuel switching resources dependent on the price forecast for natural gas.

the actors from whom it should be measured, such as the electric utility, a utility customer, or society as a whole (Krause and Eto 1988). We adopt the societal perspective here.[4]

The CCE is typically compared with the national average price of electric power to residential customers (7.6¢/kWh in 1989) as a rough gauge of cost effectiveness. This simple comparison can be misleading. In principle, the cost of a conservation measure should be compared to the *utility costs avoided* by that efficiency measure, which may or may not correspond to the *average price* of electricity.

We show the cost of electricity on the supply curves for rough comparisons, but emphasize that a consistent comparison between supply and demand-side resources requires using appropriate risk-based discount rates to calculate the busbar cost of new electric supply resources (Kahn 1988), the avoided capital costs of transmission and distribution (Orens 1989), the societal value of avoided pollutant emissions and other externalities (Chernick and Caverhill 1989, Hohmeyer 1988, Koomey 1990a, Ottinger et al. 1990), and the administrative, monitoring, and overhead costs of demand-side options (Berry 1989, Krause et al. 1989). Such a comparison should be undertaken as an extension of this paper. For further discussion of such comparisons, see Krause et al. (1991).

Our analysis uses a *real discount rate, without inflation*, which results in capital costs per kWh that are lower than those calculated using nominal discount rates including inflation and taxes. The omission of taxes does not affect the cost-effectiveness comparison as long as the conservation is assumed to be purchased entirely by the residential customer or expensed by the utility (the most common method for utility programs).

Frozen efficiency baseline

Our analysis begins with a *frozen efficiency baseline*. Such a forecast assumes that equipment and buildings existing in 1990 are not retrofit during the analysis period, and remain at constant efficiency until 2010 (or until they retire). New and replacement equipment and buildings are assumed to be installed at the efficiency level of new devices in 1990, but saturations are allowed to vary over the analysis period.[5] Average energy efficiency improves in the frozen efficiency case, because of replacement of existing structures and equipment with more efficient new devices. Appliance efficiency standards due to be implemented in 1992, 1993, and 1994 are represented as measures on the supply curve.

The LBL Residential Energy Model (LBL REM) is an end-use forecasting model that we use to estimate frozen efficiency case saturations and projected unit energy consumptions (UECs) for all non-space conditioning end-uses (see LBL REM (1991) and McMahon (1986)). Saturations for space conditioning end-uses are taken from US DOE (1989a) and UECs for these end-uses are calculated directly from our building prototypes. LBL REM does not currently contain sufficient detail on space conditioning end-uses to use the saturations and UECs from its frozen efficiency case.

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[4]The discount rate we use (7% real) is probably high for a societal analysis, since the real rate of interest on long-term treasury notes averages 3-4% real. The real return on investment for electric utilities has averaged 5-7% real in the last decade (Koomey 1990b), and since utility resources would be avoided by our efficiency investments, we chose 7%. Reducing the discount rate to 3% would decrease the cost of conserved energy by 29%.

[5]Non-space conditioning saturations have been taken from LBL REM (1991) and vary over time. Space conditioning saturations do not vary in our analysis.

Technical conservation potential

This study estimates the *technical potential*, which is defined by Krause et al. (1987) as the amount of energy savings that could be achieved if all households install the most efficient devices, without considering lag times and other practical constraints associated with real-world programs. Level of service is kept constant in this analysis.

Achievable conservation potential

In practice, the technical potential is an upper limit to the amount of efficiency that can be captured by utilities. Markets will eventually capture part of this technical potential, though information barriers, capital constraints, risk aversion, bounded rationality, satisficing behavior, regulatory distortions, and other market failures prevent the market from capturing it all. Some of these market failures can be partially or totally overcome, which would allow some fraction of the technical potential to be captured by utility or government programs (Koomey 1990b).

To reflect utility program costs, the societal cost of conserved energy should be increased by 10 to 20% (Berry 1989, Krause et al. 1987, Nadel 1990, NPPC 1989).[6] We do not include this cost here, because we are estimating the technical potential. *However, analysts who use our technical potential estimates to derive achievable potential* ***must*** *include this cost.*

Summary

Figure 1, adopted from Krause et al. (1987), shows schematically how the frozen efficiency baseline compares to the technical potential case as well as to a hypothetical achievable potential case. Only the frozen efficiency baseline and technical potential cases are included in this analysis. The business as usual case with no additional policies represents what will happen given existing regulations and market forces (it includes appliance efficiency standards scheduled to take effect in 1992, 1993, and 1994, and the effect of exogenous changes in electricity prices).

B. Definitions and general assumptions

This section describes the major assumptions adopted for this analysis. For more details on terminology, assumptions, or calculational methods, see Appendix 10.

Discount rate and inflation

The discount rate is 7% real. All costs are expressed in constant 1989 dollars, net of inflation.

[6]20% is a conservative number based on experience with current programs, while 10% implies some economies of scale and learning curve effects that would be captured by aggressive programs. Program costs for particular end-uses may be lower or higher than these crude averages (individual programs for specific end-uses may differ from these overall averages).

Figure 1: Relationship Between Frozen Efficiency and Maximum Technical Potential

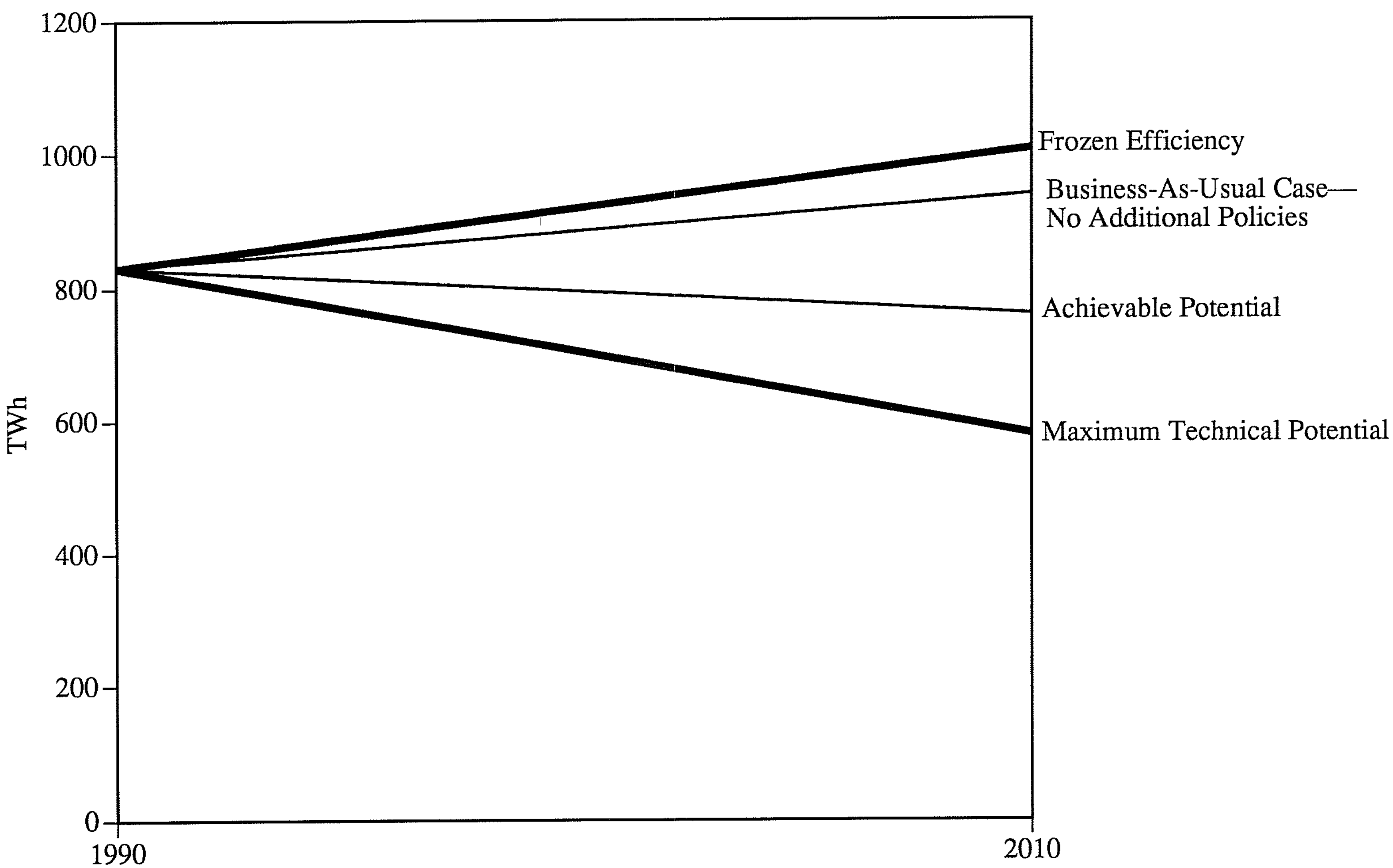


Figure adopted from Krause et al. (1987)

Analysis period

We consider the potential for energy efficiency improvements over the period 1990 to 2010. As longer time horizons are considered, potential savings increase but uncertainty about input parameters also increases.

Conservation costs

All costs are installed costs to the consumer. Space conditioning equipment and building shell improvement costs represent the cost of contractor installation. *No utility or government administrative costs are included.*

Retrofits and replacements

Shell retrofits are assumed to occur at a rate sufficient to retrofit all such shells by 2010. Replacement of existing equipment and appliances varies depending on the device lifetime. For an appliance with a ten year lifetime, 10% (1/10) of the equipment existing in 1990 is replaced each year. This replacement rate is linear, not exponential, and is only a crude approximation to actual retirement rates.

Technical potential

When calculating the technical potential for efficiency improvements, installation of conservation measures is affected solely by physical constraints. This convention becomes problematic when advanced technology options are considered that do not currently have substantial market shares and that would require major increases in production volume. For example, the logistic constraints involved in increasing production of heat pump water heaters are both physical and economic, and estimating how many could be produced is not solely a technical problem (see below). We attempt to account for these constraints by giving a *date of introduction* to advanced technologies.

Savings

Energy savings are calculated relative to the frozen efficiency baseline, assuming that level of service remains constant. Savings are measured at the customer's meter, and do not include the roughly 5-8% in avoided transmission and distribution losses from delivering the electricity. These losses must be included when comparing power plants to energy efficiency resources.

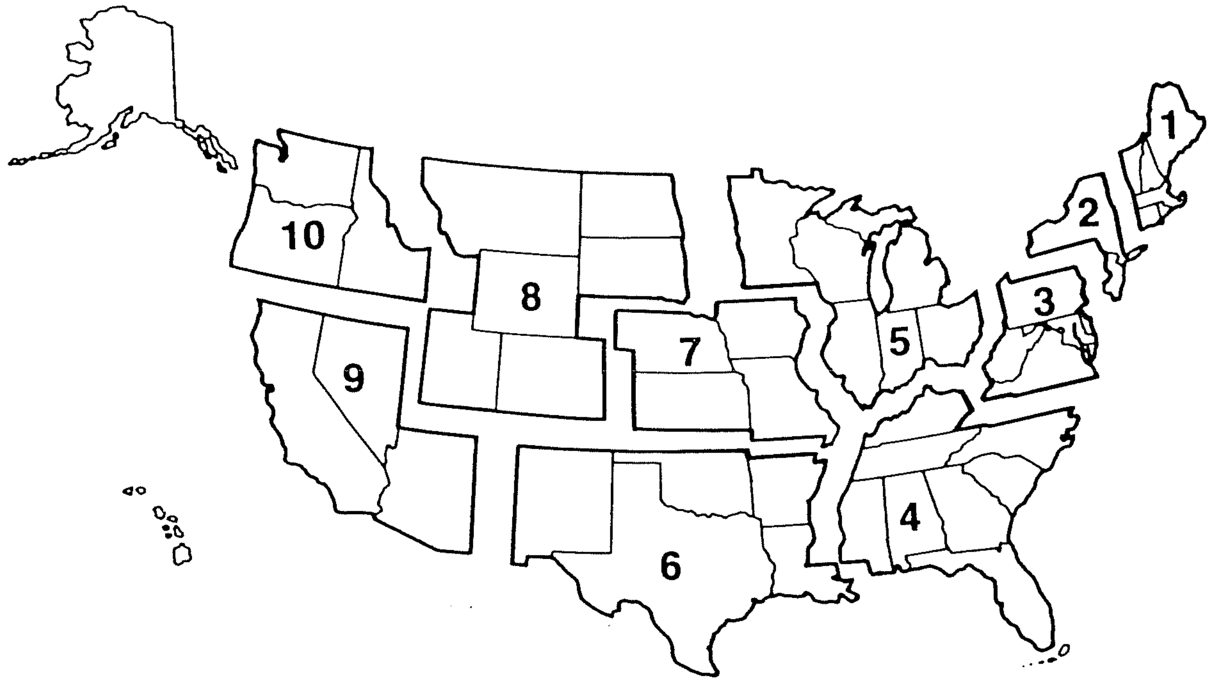
C. Frozen efficiency baseline forecast

Defining the frozen efficiency baseline estimate of energy consumption is a difficult but crucial exercise, because energy savings depend directly upon this baseline. If the baseline estimate is biased in one direction or another, the energy savings will be correspondingly affected The following section briefly describes the characteristics of our baseline forecast.

Regional disaggregation

We treat the U.S. as two distinct regions (north and south), but present the results for the U.S. as a whole. The south region is composed of the states in Federal (US DOE) regions 4, 6, and 9, while the north region is composed of the states in Federal regions 1, 2, 3, 5, 7, 8, and 10. **Figure 2** shows these regions.

Figure 2: Federal Regions



Region 1
New England
Connecticut (CT)
Maine (ME)
Massachusetts (MA)
New Hampshire (NH)
Rhode Island (RI)
Vermont (VT)

Region 2
New York/
New Jersey
New Jersey (NJ)
New York (NY)

Region 3
Mid Atlantic
Delaware (DE)
District of Columbia (DC)
Maryland (MD)
Pennsylvania (PA)
Virginia (VA)
West Virginia (WV)

Region 4
South Atlantic
Alabama (AL)
Florida (FL)
Georgia (GA)
Kentucky (KY)
Mississippi (MS)
North Carolina (NC)
South Carolina (SC)
Tennessee (TN)

Region 5
Midwest
Illinois (IL)
Indiana (IN)
Michigan (MI)
Minnesota (MN)
Ohio (OH)
Wisconsin (WI)

Region 6
Southwest
Arkansas (AR)
Louisiana (LA)
New Mexico (NM)
Oklahoma (OK)
Texas (TX)

Region 7
Central
Iowa (IA)
Kansas (KS)
Missouri (MO)
Nebraska (NE)

Region 8
North Central
Colorado (CO)
Montana (MT)
North Dakota (ND)
South Dakota (SD)
Utah (UT)
Wyoming (WY)

Region 9
West
Arizona (AZ)
California (CA)
Hawaii (HI)
Nevada (NV)

Region 10
Northwest
Alaska (AK)
Idaho (ID)
Oregon (OR)
Washington (WA)

South Region is defined as Federal Regions 4, 6, and 9.

North Region is defined as Federal Regions 1, 2, 3, 5, 7, 8, and 10

Housing starts and retirements

Table 1 shows housing starts and stocks for the U.S. as a whole, and **Tables 2 and 3** show housing units for the north and south regions, respectively. Single-family homes dominate the total, comprising about 67% of homes in the U.S. About two thirds of single/multi-family homes existing in 1990 will remain in 2010, while only one third of mobile homes existing in 1990 will remain in 2010 (due to their relatively short lifetimes). Annual percentage growth in single-family and multi-family homes is slightly higher in the south than in the north. Mobile homes are projected to grow more quickly in percentage terms than are single-family or multi-family homes, but this growth is exclusively in the southern region. Stocks and forecasts are from LBL REM (1991) and MHI (1989, 1990, 1991b)

Building and equipment lifetimes

Table 4 shows lifetimes for space conditioning equipment, appliances, and building shells. These lifetimes are used to estimate the rate of stock turnover of these devices, and to calculate the cost of conserved energy. Major appliances range in lifetime from 12 years for central air conditioners to 23 years for furnaces.

Weather

Estimates of space conditioning energy use rely on building energy simulation programs that use weather files for representative U.S. cities. We estimated the population-weighted average weather for the north and south regions of the U.S. using a climate averaging program (GLOM) developed at Lawrence Berkeley Laboratory (Andersson et al. 1986). GLOM revealed that Chicago, Illinois approximates average weather for the north, and Charleston, SC approximates the weather for the south.[7] In cases where weather files for these two cities were not available (e.g., when using data from Ritschard and Huang for multifamily prototypes), we used the next closest cities and adjusted space conditioning energy consumption by ratios of heating degree days and cooling degree days.

Thermal characteristics of buildings

Table 5 shows average shell characteristics of new and existing residential buildings, based on a variety of sources (Boghosian 1991, Koomey et al. 1991, Lee 1991, MHI 1991a, MHI 1991b, Mills 1984). When possible, characteristics have been compared to and made consistent with those found in the U.S. Department of Energy's Residential Energy Consumption Surveys (RECS) (US DOE 1984, US DOE 1989a). These characteristics are then input to our building energy simulation program (see Appendix 7 for the detailed input files to this program).

Floor area: Table 5 shows that average floor areas are uniformly larger for new buildings than for existing buildings.

Ceiling insulation: Average ceiling insulation levels range from R-17 to R-24 for existing single-family (SF) dwellings, and from R-25 to R-29 for new SF buildings. Ceiling insulation levels for existing mobile homes (MHs) are significantly lower than for

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[7]Heating degree days for Chicago and Charleston (65 degrees F base) are 6125 and 2146, respectively. Cooling degree days (65 degrees F base) are 923 and 2077, respectively.

Table 1: Existing and forecasted housing units in the United States									
in millions of units	*1990*	*1995*	*2000*	*2005*	*2010*	*Annual % growth 1990-2010*	*Total % growth 1990-2010*	*Average annual Δ units (x10^6) 1990-2010*	*Total Δ units (x10^6) 1990-2010*
Single-family total	*63.3*	*67.9*	*72.3*	*76.6*	*78.5*	1.1%	24.1%	0.76	15.23
Existing (1990)	63.3	61.0	58.6	56.0	53.3	-0.9%	-15.8%	-0.50	-10.01
New (post 1990)	0.0	6.9	13.7	20.6	25.2	N/A	N/A	1.26	25.24
Multi-family total	*26.5*	*28.4*	*30.3*	*32.1*	*32.9*	1.1%	24.1%	0.32	6.38
Existing (1990)	26.5	25.5	24.3	23.1	21.8	-1.0%	-17.6%	-0.23	-4.67
New (post 1990)	0.0	3.0	6.0	9.0	11.1	N/A	N/A	0.55	11.05
Mobile homes total	*4.2*	*4.6*	*5.1*	*5.8*	*6.5*	2.2%	55.3%	0.12	2.3
Existing (1990)	4.2	3.5	3.0	2.6	2.2	-3.2%	-47.8%	-0.10	-1.99
New (post 1990)	0.0	1.0	2.1	3.3	4.3	N/A	N/A	0.21	4.29
Total	94.0	100.9	107.7	114.5	117.9	1.1%	25.4%	1.20	23.91
As % of house type totals									
Single-family total	*100%*	*100%*	*100%*	*100%*	*100%*	0.0%	0.0%		
Existing (1990)	100%	90%	81%	73%	68%	-1.9%	-32.1%		
New (post 1990)	0%	10%	19%	27%	32%	N/A	N/A		
Multi-family total	*100%*	*100%*	*100%*	*100%*	*100%*	0.0%	0.0%		
Existing (1990)	100%	90%	80%	72%	66%	-2.0%	-33.6%		
New (post 1990)	0%	10%	20%	28%	34%	N/A	N/A		
Mobile homes total	*100%*	*100%*	*100%*	*100%*	*100%*	0.0%	0.0%		
Existing (1990)	100%	77%	59%	44%	34%	-5.3%	-66.4%		
New (post 1990)	0%	23%	41%	56%	66%	N/A	N/A		
As % of total units									
Single-family total	*67%*	*67%*	*67%*	*67%*	*67%*	-0.1%	-1.1%		
Existing (1990)	67%	60%	54%	49%	45%	-2.0%	-32.9%		
New (post 1990)	0%	7%	13%	18%	21%	N/A	N/A		
Multi-family total	*28%*	*28%*	*28%*	*28%*	*28%*	-0.1%	-1.1%		
Existing (1990)	28%	25%	23%	20%	19%	-2.1%	-34.3%		
New (post 1990)	0%	3%	6%	8%	9%	N/A	N/A		
Mobile homes total	*4%*	*5%*	*5%*	*5%*	*5%*	1.1%	23.8%		
Existing (1990)	4%	4%	3%	2%	2%	-4.3%	-58.4%		
New (post 1990)	0%	1%	2%	3%	4%	N/A	N/A		
Total	*100%*	*100%*	*100%*	*100%*	*100%*				

(1) Single family and multi family stocks are from LBL Residential Energy Model federal region projections of existing stock and additions.
(2) Mobile home 1990 stock is from MHI data for year-round occupied MHs with no permanent room attached (Census data treats MHs with permanent rooms as SF homes), updated to 1990 from 1989 using REM. We assume an exponential retirement rate of 3% per year, from MHI's average lifetime of 33.8 years. Of U.S. mobile homes existing in 1990, 42% are in the north and 58% in the south (MHI 1989).
(3) Mobile home additions are from REM national projections. We assume the fraction of additions in the north and south in 1989 (derived from MHI data) remain constant. 82% of new mobile homes are projected to be built in the south and 18% are projected to be built in the north.

Table 2: Existing and forecasted housing units in the north									
in millions of units	*1990*	*1995*	*2000*	*2005*	*2010*	*Annual % growth 1990-2010*	*Total % growth 1990-2010*	*Average annual Δ units (x10^6) 1990-2010*	*Total Δ units (x10^6) 1990-2010*
Single-family total	*35.0*	*37.3*	*39.5*	*41.6*	*42.3*	1.0%	21.1%	0.37	7.36
Existing (1990)	35.0	33.7	32.4	31.0	29.5	-0.8%	-15.6%	-0.27	-5.47
New (post 1990)	0.0	3.6	7.1	10.6	12.8	N/A	N/A	0.64	12.83
Multi-family total	*16.6*	*17.6*	*18.7*	*19.7*	*20.0*	1.0%	21.0%	0.17	3.47
Existing (1990)	16.6	15.9	15.2	14.4	13.7	-1.0%	-17.4%	-0.14	-2.88
New (post 1990)	0.0	1.8	3.5	5.2	6.4	N/A	N/A	0.32	6.35
Mobile homes total	*1.8*	*1.7*	*1.6*	*1.7*	*1.7*	-0.2%	-4.6%	0.00	-0.08
Existing (1990)	1.8	1.5	1.3	1.1	0.9	-3.2%	-48.0%	-0.04	-0.84
New (post 1990)	0.0	0.2	0.4	0.6	0.8	N/A	N/A	0.04	0.76
Total	53.3	56.6	59.8	62.9	64.0	0.9%	20.2%	0.54	10.75
As % of house type totals									
Single-family total	*100%*	*100%*	*100%*	*100%*	*100%*	0.0%	0.0%		
Existing (1990)	100%	90%	82%	74%	70%	-1.8%	-30.3%		
New (post 1990)	0%	10%	18%	26%	30%	N/A	N/A		
Multi-family total	*100%*	*100%*	*100%*	*100%*	*100%*	0.0%	0.0%		
Existing (1990)	100%	90%	81%	73%	68%	-1.9%	-31.7%		
New (post 1990)	0%	10%	19%	27%	32%	N/A	N/A		
Mobile homes total	*100%*	*100%*	*100%*	*100%*	*100%*	0.0%	0.0%		
Existing (1990)	100%	89%	77%	65%	54%	-3.0%	-45.5%		
New (post 1990)	0%	11%	23%	35%	46%	N/A	N/A		
As % of total units									
Single-family total	*66%*	*66%*	*66%*	*66%*	*66%*	0.0%	0.7%		
Existing (1990)	66%	60%	54%	49%	46%	-1.8%	-29.8%		
New (post 1990)	0%	6%	12%	17%	20%	N/A	N/A		
Multi-family total	*31%*	*31%*	*31%*	*31%*	*31%*	0.0%	0.7%		
Existing (1990)	31%	28%	25%	23%	21%	-1.9%	-31.3%		
New (post 1990)	0%	3%	6%	8%	10%	N/A	N/A		
Mobile homes total	*3%*	*3%*	*3%*	*3%*	*3%*	-1.1%	-20.6%		
Existing (1990)	3%	3%	2%	2%	1%	-4.1%	-56.7%		
New (post 1990)	0%	0%	1%	1%	1%	N/A	N/A		
Total	*100%*	*100%*	*100%*	*100%*	*100%*				

(1) North is defined as Federal regions 1, 2, 3, 5, 7, 8, and 10.
(2) Single family and multi family stocks are from LBL Residential Energy Model federal region projections of existing stock and additions.
(3) Mobile home 1990 stock is from MHI data for year-round occupied MHs with no permanent room attached (Census data treats MHs with permanent rooms as SF homes), updated to 1990 from 1989 using REM. We assume an exponential retirement rate of 3% per year, from MHI's average lifetime of 33.8 years. Of U.S. mobile homes existing in 1990, 42% are in the north and 58% in the south (MHI 1989).
(4) Mobile home additions are from REM national projections. We assume the fraction of additions in the north and south in 1989 (derived from MHI data) remain constant. 82% of new mobile homes are projected to be built in the south and 18% are projected to be built in the north.

Table 3: Existing and forecasted housing units in the south									
in millions of units	*1990*	*1995*	*2000*	*2005*	*2010*	*Annual % growth 1990-2010*	*Total % growth 1990-2010*	*Average annual Δ units (x10^6) 1990-2010*	*Total Δ units (x10^6) 1990-2010*
Single-family total	*28.3*	*30.6*	*32.8*	*35.0*	*36.2*	1.2%	27.8%	0.39	7.87
Existing (1990)	28.3	27.3	26.2	25.0	23.8	-0.9%	-16.0%	-0.23	-4.54
New (post 1990)	0.0	3.3	6.6	10.0	12.4	N/A	N/A	0.62	12.41
Multi-family total	*10.0*	*10.8*	*11.6*	*12.4*	*12.9*	1.3%	29.2%	0.15	2.91
Existing (1990)	10.0	9.6	9.1	8.7	8.2	-1.0%	-18.0%	-0.09	-1.79
New (post 1990)	0.0	1.2	2.5	3.8	4.7	N/A	N/A	0.24	4.7
Mobile homes total	*2.4*	*2.9*	*3.5*	*4.2*	*4.8*	3.5%	98.8%	0.12	2.38
Existing (1990)	2.4	2.1	1.8	1.5	1.3	-3.2%	-47.7%	-0.06	-1.15
New (post 1990)	0.0	0.9	1.8	2.7	3.5	N/A	N/A	0.18	3.53
Total	40.7	44.3	47.9	51.6	53.9	1.4%	32.3%	0.66	13.16
As % of house type totals									
Single-family total	*100%*	*100%*	*100%*	*100%*	*100%*	0.0%	0.0%		
Existing (1990)	100%	89%	80%	71%	66%	-2.1%	-34.3%		
New (post 1990)	0%	11%	20%	29%	34%	N/A	N/A		
Multi-family total	*100%*	*100%*	*100%*	*100%*	*100%*	0.0%	0.0%		
Existing (1990)	100%	89%	79%	70%	63%	-2.2%	-36.5%		
New (post 1990)	0%	11%	21%	30%	37%	N/A	N/A		
Mobile homes total	*100%*	*100%*	*100%*	*100%*	*100%*	0.0%	0.0%		
Existing (1990)	100%	70%	50%	36%	26%	-6.5%	-73.7%		
New (post 1990)	0%	30%	50%	64%	74%	N/A	N/A		
As % of total units									
Single-family total	*70%*	*69%*	*68%*	*68%*	*67%*	-0.2%	-3.4%		
Existing (1990)	70%	62%	55%	49%	44%	-2.2%	-36.5%		
New (post 1990)	0%	7%	14%	19%	23%	N/A	N/A		
Multi-family total	*24%*	*24%*	*24%*	*24%*	*24%*	-0.1%	-2.4%		
Existing (1990)	24%	22%	19%	17%	15%	-2.4%	-38.0%		
New (post 1990)	0%	3%	5%	7%	9%	N/A	N/A		
Mobile homes total	*6%*	*7%*	*7%*	*8%*	*9%*	2.1%	50.2%		
Existing (1990)	6%	5%	4%	3%	2%	-4.5%	-60.5%		
New (post 1990)	0%	2%	4%	5%	7%	N/A	N/A		
Total	*100%*	*100%*	*100%*	*100%*	*100%*				

(1) South is defined as Federal regions 4,6, and 9

(2) Single family and multi family stocks are from LBL Residential Energy Model federal region projections of existing stock and additions.

(3) Mobile home 1990 stock is from MHI data for year-round occupied MHs with no permanent room attached (Census data treats MHs with permanent rooms as SF homes), updated to 1990 from 1989 using REM. We assume an exponential retirement rate of 3% per year, from MHI's average lifetime of 33.8 years. Of U.S. mobile homes existing in 1990, 42% are in the north and 58% in the south (MHI 1989).

(4) Mobile home additions are from REM national projections. We assume the fraction of additions in the north and south in 1989 (derived from MHI data) remain constant. 82% of new mobile homes are projected to be built in the south and 18% are projected to be built in the north.

Table 4: Lifetimes of buildings, equipment, and shell measures

End use	*Average lifetime years*
Central space heating (electric)	23
Room air conditioners (RAC)	15
Central air conditioners (CAC)	12
Heat pump	14
Water heater (electric, gas)	13
Refrigerator	19
Freezer	21
Range/oven (electric, gas)	18
Dryer (electric, gas)	17
Lighting (2)	15
Dishwasher	12.6
Clothes washer	14.1
Miscellaneous	15
All building shell conservation measures	30
Single-family buildings	98
Multi-family buildings	89
Mobile homes	33.8

(1) source: LBL REM (1991), except for mobile homes, which are from MHI (1990)
(2) This is an artificial lifetime chosen for use in the ACCESS program. Actual equipment lifetimes are normalized to 15 years (see Appendix 6).

Table 5: Characteristics of baseline residential building prototypes

	Htg Type	*Region*	*Floor area per unit square feet*	*Insulation levels* Ceiling	Wall	Floor	*Infiltration ACH*	*window layers*
Existing single-family homes	elec res	North	1582	R-20.8	R-4.7	R-11	0.54	1.76
	elec res	South	1470	R-18	R-3.9	R-1.48, 2ft	0.71	1.53
	heat pump	North	1853	R-24	R-6.8	R-11	0.45	1.72
	heat pump	South	1784	R-21.5	R-6.2	R-1.68, 2ft	0.7	1.65
	non-elec	North	1550	R-21.1	R-2.1	R-11	0.62	1.79
	non-elec	South	1467	R-17.4	R-2.1	R-0.78, 2ft	0.72	1.44
New single-family homes	elec res	North	1856	R-29	R-15	R-15	0.4	2
	elec res	South	1894	R-28	R-10	R-3.8, 2ft	0.62	1.51
	heat pump	North	2222	R-28	R-14	R-13	0.4	1.87
	heat pump	South	1823	R-25	R-11	R-1.8, 2ft	0.63	1.69
	non-elec	North	2177	R-28	R-14	R-12	0.56	1.74
	non-elec	South	2071	R-25	R-12	R-1.9, 2ft	0.63	1.68
Multifamily Existing		North	1051	R-7	R-5			2
		South	945	R-4	R-2			1
New		North	1050	R-30	R-13			2
		South	968	R-21	R-12			2
Mobile homes Existing	elec res	North	1025	R-14.2	R-10.8	R-10.8	0.45	2
	elec res	South	940	R-10.8	R-10.8	R-6.8	0.56	1
	heat pump	North	800	R-14.2	R-10.8	R-10.8	0.45	2
	heat pump	South	1040	R-10.8	R-10.8	R-6.8	0.56	1
	non-elec	North	804	R-14.2	R-10.8	R-10.8	0.45	2
	non-elec	South	847	R-10.8	R-10.8	R-6.8	0.56	1
New		North	1195	R-26	R-18	R-14	0.36	2
		South	1195	R-20	R-12	R-10	0.45	1.26

(1) Building shell and infiltration characteristics for existing SF homes are from 1984 RECS (Boghosian 1991), updated to 1990 using the 1987 NAHB new home database (as summarized in Koomey et al. 1991). New SF home characteristics are from Koomey et al 1991.
(2) Floor insulation for the SF in the south is slab edge insulation to the R-value specified, to a depth of 2 feet. Floor insulation for SF existing in north is assumed to be R-11, as a conservatism. Floor conservation measures are only applied to unheated crawl spaces and basements for existing homes in the north.
(3) MF characteristics are averaged from Ritschard and Huang (1989), using 5 prototype buildings in Fort Worth for the south, and 4 prototypes in Chicago for the north. Ritschard and Huang do not consider prototypes for 1940s and 1950s buildings. We assume that 1940s buildings are the same as pre 1940s buildings, and that 1950s buildings are the same as 1960s buildings. Ritschard and Huang do not indicate the infiltration rates (in air changes per hour or ach) for their prototypes.
(4) Mobile home floor area is the national average for those sold in 1989, from Manufactured Housing Institute (MHI 1991b). MH infiltration rates are estimates from Allen Lee of Battelle PNL (personal communication, April 1991) of existing mobile homes in the Pacific Northwest. Lee's ACH of 0.4 was adjusted by the specific infiltration rate for our northern region in order to account for the difference in weather between Seattle and Chicago. We assumed that homes in the north and homes in Seattle would have the same specific leakage area. All other MH shell characteristics were obtained from Manufactured Housing Institute estimates of the most popular shell packages sold in 1990 by region (MHI 1991a).

Insulation levels for northern homes are uniformly higher than for southern homes.

Wall insulation: Just as for ceiling insulation, wall insulation in new buildings substantially exceeds that typically found in existing buildings. The wall insulation levels of structures in the north always equal or exceed those in the south.

Foundation characteristics: Other thermal integrity characteristics are amenable to averaging, while foundations are difficult to characterize because of the many different foundation types and methods of insulating them. Boghosian (1991) has attempted to overcome this problem using a "U" value per linear foot approach, but for simplicity, we have assumed that single family dwellings in the north have an unheated basement (with floor insulation of R-11, to be conservative), while SF dwellings in the south are slab homes. This assumption corresponds to the most commonly used foundations in homes in these regions.

Infiltration: Existing data on infiltration are poor. The infiltration rates used in this analysis were derived from Boghosian (1991), Koomey et al. (1991), and Lee (1991). Duct leakage, which can be substantial in centrally-conditioned homes (Brook 1991, Cummings et al. 1990), has not been included in the analysis due to lack of data. See the discussion below of *Improvements to the Analysis* (Part IV) for more explicit analysis of the potential effects of duct leakage.

Windows: Table 5 gives the average number of window panes for the building prototypes. Averaging the number of window panes in this manner will become a less and less reliable measure of window U-value as special coatings and noble-gas filled spaces between panes become commonplace. The estimates for SF buildings in Boghosian (1991) and Koomey et al. (1991) rely on data sources that do not distinguish windows by these special characteristics. No effort has been made to correct for this effect.

We have used the costs and thermal characteristics of triple pane windows and double pane low-emissivity windows interchangeably in this report. This assumption is probably conservative, since the cost of coatings is likely to decrease much faster than the costs of making a triple glazed window.

Space conditioning energy use

Tables 6 through 11 show space conditioning saturations, efficiencies, and unit energy consumptions (UECs) for existing and new single-family, multi-family, and mobile homes, respectively. Saturations for space conditioning equipment in existing homes are taken from US DOE (1989a). Saturations for new homes are from the same source, and represent a weighted average over all homes built 1980 to 1988, weighted using 1988 housing starts from Census (1990). Space conditioning UECs have been calculated using the batch version of PEAR (Program for the Energy Analysis of Residences), which is a residential building simulation model developed at Lawrence Berkeley Laboratory (EAP 1987). We have estimated the UECs and conservation potential separately for each combination of heating and cooling equipment, using the shell characteristics shown in Table 5 and equipment efficiencies from our national database (LBL 1990). Room air conditioner (RAC) UECs have been estimated from PEAR's central air conditioner (CAC) UECs by using regional ratios (adjusted to our north/south regions) of RAC UEC to CAC UEC from RCG/Hagler Bailly (1990).

Table 6: Heating and cooling of existing single-family buildings: saturations, efficiency, and electricity consumption

North Enduse Code	*Htg/Clg Type*	*% of all SF homes*	*Existing Htg/Clg Efficiency*	*Existing Htg UEC kWh/yr*	*Existing Clg UEC kWh/yr*	*Replacement Htg/Clg Efficiency*	*Replacement Htg UEC kWh/yr*	*Replacement Clg UEC kWh/yr*
ESNE	ER/ -	2%	100% / -	18311	0	100% / -	18311	0
ESNEC	ER/ CAC	2%	100% / 8.62 SEER	18311	1138	100% / 9.96 SEER	18311	985
ESNER	ER / RAC	2%	100% / 7.47 EER	18311	368	100% / 9.0 EER	18311	305
ESNHP	HP	3%	6.79 HSPF/ 8.59 SEER	9300	1176	7.24 HSPF/ 9.86 SEER	8722	1025
ESNG*	Gas-Other / -	38%	- / -	0	0	- / -	0	0
ESNGC*	Gas-Other / CAC	23%	- / 8.62 SEER	0	1162	- / 9.96 SEER	0	1006
ESNGR*	Gas-Other / RAC	29%	- / 7.47 EER	0	376	- / 9.0 EER	0	312
Total		100%						

South Enduse Code	*Htg/Clg Type*	*% of all SF homes*	*Existing Htg/Clg Efficiency*	*Existing Htg UEC kWh/yr*	*Existing Clg UEC kWh/yr*	*Replacement Htg/Clg Efficiency*	*Replacement Htg UEC kWh/yr*	*Replacement Clg UEC kWh/yr*
ESSE	ER/ -	3%	100% / -	8201	0	100% / -	8201	0
ESSEC	ER/ CAC	6%	100% / 8.62 SEER	8201	3739	100% / 9.96 SEER	8201	3236
ESSER	ER / RAC	3%	100% / 7.47 EER	8201	1325	100% / 9.0 EER	8201	1100
ESSHP	HP	8%	6.79 HSPF/ 8.59 SEER	4394	4077	7.24 HSPF/ 9.86 SEER	4121	3552
ESSG*	Gas-Other / -	33%	0	0	0	- / -	0	0
ESSGC*	Gas-Other / CAC	23%	- / 8.62 SEER	0	3842	- / 9.96 SEER	0	3325
ESSGR*	Gas-Other / RAC	24%	- / 7.47 EER	0	1362	- / 9.0 EER	0	1131
Total		100%						

* for baseline energy consumption only (no shell measures included). HP = heat pump; ER=electric resistance; CAC/RAC= central or room air conditioners

(1) All shell characteristics are from Boghosian, 1991 and are derived from RECS84 data updated to 1990 levels using the NAHB new home database created in Koomey et. al., 1991 (see Table 5 for more details). Due to time constraints, no foundation insulation measures for existing homes were included.
(2) Window area is assumed to be 10% of floor area.
(3) The saturations of heating/cooling types are from RECS87 Census region data converted to federal regions using 1980 Census state-by-state data.
(4) Equipment efficiencies are from LBL REM (1990 new unit and 1990 existing unit average efficiencies), based on extrapolation from 1987 ARI data.
(5) All UECs are from PEAR except for the room air conditioner UEC, which is assumed to be 34% of the PEAR-derived central air conditioner UEC. Room AC UEC was derived as a fraction of CAC UEC from utility data provided in RCG/Hagler Bailly Inc. (1990).
All UECs for the north are based on a single story prototype home in Chicago, IL with unheated basement.
All UECs for the south are based on a single story prototype home in Charleston, SC with slab foundation.
(6) Existing homes have two UECs. The "existing" UEC is calculated using the existing shell characteristics and the 1990 existing equipment efficiency from the LBL Residential Energy Model (LBL REM). The "replacement" UEC is calculated using the existing shell and the 1990 new unit efficiency from LBL REM.
(7) Furnace fan electricity use for non-electric furnaces is counted under the "Other" end-use category, and does not appear in this table.
(8) HP = heat pump; ER=electric resistance; CAC/RAC= central or room air conditioners

Table 7: **Heating and cooling of new single-family buildings: saturations, efficiency, and electricity consumption**

North Enduse Code	*Htg/Clg Type*	*% of all new SF homes*	*Htg/Clg Efficiency*	*Htg UEC kWh/yr*	*Clg UEC kWh/yr*
NSNE	ER/ -	7%	100%/ -	11809	0
NSNEC	ER/CAC	6%	100%/9.96 SEER	11809	964
NSNER	ER/RAC	2%	100%/9.0 EER	11809	299
NSNHP	HP/HP	17%	7.24 HSPF /9.86 SEER	6825	1048
NSNG*	Gas-Other / -	28%	- / -	0	0
NSNGC*	Gas-Other /CAC	31%	- /9.96 SEER	0	1042
NSNGR*	Gas-Other /RAC	9%	- /9.0 EER	0	323
Total		*100%*			

South Enduse Code	*Htg/Clg Type*	*% of all new SF homes*	*Htg/Clg Efficiency*	*Htg UEC kWh/yr*	*Clg UEC kWh/yr*
NSSE	ER/ -	5%	100%/ -	9114	0
NSSEC	ER/CAC	12%	100%/9.96 SEER	9114	3583
NSSER	ER/RAC	3%	100%/9.0 EER	9114	1218
NSSHP	HP/HP	26%	7.24 HSPF /9.86 SEER	3225	3408
NSSG*	Gas-Other / -	28%	- / -	0	0
NSSGC*	Gas-Other /CAC	20%	- /9.96 SEER	0	3576
NSSGR*	Gas-Other /RAC	7%	- /9.0 EER	0	1216
Total		*100%*			

* for baseline energy consumption only (no shell measures included). HP = heat pump; ER=electric resistance; CAC/RAC= central or room air conditioners

(1) All shell characteristics are from Koomey, et.al 1991. The characteristics were weighted by 1987 housing starts in the relevant federal regions.

(2) Window area is assumed to be 10% of floor area.

(3) The saturations of heating/cooling types are from RECS87 Census region data for homes built 1980-88, converted to federal regions using 1989 state-by-state housing start data from the 1990 Statistical Abstract of the United States.

(4) Equipment efficiencies are from LBL REM (1991) for 1990 new units (based on an extrapolation from 1987 ARI data).

(5) All new homes in the north are assumed to be two-story, basement foundation types, and in the south one-story, slab foundation types. These are the predominant configurations in these regions (from the NAHB new home database created in Koomey et.al., 1991).

(6) All UECs are from PEAR except for the room air conditioner UEC, which is assumed to be 34% of the PEAR-derived central air conditioner UEC. Room AC UEC was derived as a fraction of CAC UEC from utility data provided in RCG/Hagler Bailly Inc. 1990. Chicago weather was used for the northern prototype, and Charleston, SC weather for the southern prototype.

(7) Furnace fan electricity use for non-electric furnaces is counted as "miscellaneous energy" and does not appear in this table.

(8) HP = heat pump; ER=electric resistance; CAC/RAC= central or room air conditioners

Table 8: Heating and cooling of existing multi-family buildings: saturations, efficiency, and electricity consumption

North Enduse Code	*Htg/Clg Type*	*% of all SF homes*	*Existing Htg/Clg Efficiency*	*Existing Htg UEC kWh/yr*	*Existing Clg UEC kWh/yr*	*Replacement Htg/Clg Efficiency*	*Replacement Htg UEC kWh/yr*	*Replacement Clg UEC kWh/yr*
EANE	ER / -	5%	100% / -	11701	0	100% / -	11701	0
EANEC	ER / CAC	5%	100% / 8.62 SEER	11701	515	100% / 9.96 SEER	11701	446
EANER	ER / RAC	5%	100% / 7.47 EER	11701	160	100% / 9.0 EER	11701	138
EANHP	HP	2%	6.79 HSPF/ 8.59 SEER	5882	517	7.24 HSPF/ 9.86 SEER	5516	451
EANG	Gas-Other / -	42%	- / -	0	0	- / -	0	0
EANGC	Gas-Other / CAC	10%	- / 8.62 SEER	0	515	- / 9.96 SEER	0	446
EANGR	Gas-Other / RAC	32%	- / 7.47 EER	0	160	- / 9.0 EER	0	138
Total		*100%*						

South Enduse Code	*Htg/Clg Type*	*% of all SF homes*	*Existing Htg/Clg Efficiency*	*Existing Htg UEC kWh/yr*	*Existing Clg UEC kWh/yr*	*Replacement Htg/Clg Efficiency*	*Replacement Htg UEC kWh/yr*	*Replacement Clg UEC kWh/yr*
EASE	ER / -	13%	100% / -	3026	0	100% / -	3026	0
EASEC	ER / CAC	16%	100% / 8.62 SEER	3026	1366	100% / 9.96 SEER	3026	1182
EASER	ER / RAC	8%	100% / 7.47 EER	3026	424	100% / 9.0 EER	3026	367
EASHP	HP	7%	6.79 HSPF/ 8.59 SEER	1521	1371	7.24 HSPF/ 9.86 SEER	1427	1194
EASG	Gas-Other / -	29%	- / -	0	0	- / -	0	0
EASGC	Gas-Other / CAC	14%	- / 8.62 SEER	0	1366	- / 9.96 SEER	0	1182
EASGR	Gas-Other / RAC	14%	- / 7.47 EER	0	424	- / 9.0 EER	0	367
Total		*100%*						

(1) UECs were obtained from heating and cooling loads (Ritschard & Huang, 1989) for 5 prototype buildings of different vintage located in Chicago for the north, and Fort Worth for the south (Fort Worth weather adjusted to Charleston, SC weather using ratios of degree days). The vintages were weighted using data from RECS87 and the 1980 Census. Ritschard and Huang did not include prototypes for 1940s and 1950s buildings. 1940s buildings were assumed to have the same characteristics as pre-1940s buildings, and 1950s buildings were assumed to have the same characteristics as 1960s buildings.

(2) Equipment efficiencies are from LBL REM (1991) for 1990 new and existing units, based on extrapolation from 1987 ARI data.

(3) Existing homes have two UECs. The "existing" UEC is calculated using the existing shell characteristics and the 1990 existing equipment efficiency from the LBL Residential Energy Model (LBL REM). The "replacement" UEC is calculated using the existing shell but the 1990 new unit efficiency from LBL REM. Space conditioning equipment saturations are from RECS87 data. for multifamily homes and are weighted using 1980 Census MF home stocks.

(4) No shell efficiency measures are applied to multifamily buildings, only equipment efficiency measures.

(5) HP = heat pump; ER=electric resistance; CAC/RAC= central or room air conditioners

(6) Furnace fan electricity use for non-electric furnaces is counted as "miscellaneous energy" and does not appear in this table.

Table 9: Heating and cooling of new multi-family buildings: saturations, efficiency, and electricity consumption

North Enduse Code	*Htg/Clg Type*	*% of all new MF homes*	*Htg/Clg Efficiency*	*Htg UEC kWh/yr*	*Clg UEC kWh/yr*
NANE	ER / -	12%	100% / -	6768	0
NANEC	ER / CAC	20%	100% / 9.96 SEER	6768	412
NANER	ER / RAC	2%	100% / 9.0 EER	6768	128
NANHP	HP	3%	7.24 HSPF/ 9.86 SEER	3191	416
NANG	Gas-Other / -	23%	- / -	0	0
NANGC	Gas-Other / CAC	14%	- / 9.96 SEER	0	412
NANGR	Gas-Other / RAC	26%	- / 9.0 EER	0	128
Total		100%			

South Enduse Code	*Htg/Clg Type*	*% of all new MF homes*	*Htg/Clg Efficiency*	*Htg UEC kWh/yr*	*Clg UEC kWh/yr*
NASE	ER / -	13%	100% / -	862	0
NASEC	ER / CAC	30%	100% / 9.96 SEER	862	945
NASER	ER / RAC	7%	100% / 9.0 EER	862	293
NASHP	HP	12%	7.24 HSPF/ 9.86 SEER	406	955
NASG	Gas-Other / -	14%	- / -	0	0
NASGC	Gas-Other / CAC	22%	- / 9.96 SEER	0	945
NASGR	Gas-Other / RAC	2%	- / 9.0 EER	0	293
Total		*100%*			

(1) Space conditioning equipment saturations are from RECS87 data for multifamily homes built 1980-88 and are weighted using 1988 new housing starts data from the Statistical Abstract of the United States 1990.
(2) UECs were obtained from heating and cooling loads (Ritschard & Huang, 1989) for 1980s vintage buildings located in Chicago for the north and Fort Worth for the south.
(Fort Worth weather adjusted to Charleston, SC weather using ratios of degree days).
(3) Equipment efficiencies are from LBL REM (1991) for 1990 new units, based on extrapolation from 1987 ARI data.
(4) No shell efficiency measures are applied to multifamily buildings, only equipment efficiency measures.
(5) HP = heat pump; ER=electric resistance; CAC/RAC= central or room air conditioners
(6) Furnace fan electricity use for non-electric furnaces is counted as "miscellaneous energy" and does not appear in this table.

Table 10: Heating and cooling of existing mobile homes: saturations, efficiency and electricity consumption

North Enduse Code	*Htg/Clg Type*	*% of all MHs*	*Existing Htg/Clg Efficiency*	*Existing Htg UEC*	*Existing Clg UEC*	*Replacement Htg/Clg Efficiency*	*Replacement Htg UEC*	*Replacement Clg UEC*
EMNE	ER / -	3%	100% / -	11188	0	100% / -	11188	0
EMNEC	ER / CAC	3%	100% / 8.62 SEER	11188	1542	100% / 9.96 SEER	11188	1334
EMNER	ER / RAC	4%	100% / 7.47 EER	11188	478	100% / 9.0 EER	11188	414
EMNHP	HP	1%	6.79 HSPF/ 8.59 SEER	5626	1544	7.24 HSPF/ 9.86 SEER	5276	1345
EMNG	Gas-Other / -	41%	- / -	0	0	- / -	0	0
EMNGC	Gas-Other / CAC	21%	- / 8.62 SEER	0	1429	- / 9.96 SEER	0	1236
EMNGR	Gas-Other / RAC	28%	- / 7.47 EER	0	443	- / 9.0 EER	0	383
Total		*100%*						
South *Enduse Code*	*Htg/Clg Type*	*% of all MHs*	*Existing Htg/Clg Efficiency*	*Existing Htg UEC*	*Existing Clg UEC*	*Replacement Htg/Clg Efficiency*	*Replacement Htg UEC*	*Replacement Clg UEC*
EMSE	ER / -	7%	100% / -	5800	0	100% / -	5800	0
EMSEC	ER / CAC	8%	100% / 8.62 SEER	5800	3065	100% / 9.96 SEER	5800	2653
EMSER	ER / RAC	12%	100% / 7.47 EER	5800	1042	100% / 9.0 EER	5800	902
EMSHP	HP	1%	6.79 HSPF/ 8.59 SEER	2964	3175	7.24 HSPF/ 9.86 SEER	2780	2766
EMSG	Gas-Other / -	27%	- / -	0	0	- / -	0	0
EMSGC	Gas-Other / CAC	10%	- / 8.62 SEER	0	2926	- / 9.96 SEER	0	532
EMSGR	Gas-Other / RAC	34%	- / 7.47 EER	0	995	- / 9.0 EER	0	861
Total		*100%*						

(1) Room air conditioner UEC is assumed to be 31% and 34% of corresponding CAC UEC in the north and south, respectively (from NERC regional utility data--RCG/Hagler-Bailly 1990).
(2) UECs were obtained from PEAR using a prototype one-story single family home with aluminum window sashes. The PEAR results for the north were adjusted from Cincinnati weather (the nearest city to Chicago with crawl space in the PEAR database) to Chicago weather using ratios of heating and cooling degree days. PEAR results in the south are based on Charleston, SC weather.
(3) Floor areas are from RECS 1987.
(4) All shell characteristics except for infiltration correspond to HUD Zone II minimum requirements (Mills 1984) for the north, and Zone I minimum requirements for the south. HUD Zones I and II are virtually identical geographically to our South and North regions, respectively.
(5) Infiltration rates are estimates from Allen Lee of Battelle PNL (personal communication, April 1991) of existing mobile homes in the Pacific Northwest. Lee's ACH of 0.5 was adjusted by the specific infiltration rate for our northern and southern regions in order to account for the difference in weather between Seattle and Chicago (or Charleston). We assumed that our prototype homes and homes in Seattle have the same specific leakage area.
(6) The saturations of homes in each space conditioning category are from RECS 87.
(7) No shell measures are applied to mobile homes, only equipment efficiency measures.
(8) HP = heat pump; ER=electric resistance; CAC/RAC= central or room air conditioners
(9) Furnace fan electricity use for non-electric furnaces is counted as "miscellaneous energy" and does not appear in this table.
(10) Equipment efficiencies are from LBL REM (1991) for 1990 new and existing units, based on extrapolation from 1987 ARI data.

Table 11: Heating and cooling of new mobile homes: saturations, efficiency, and electricity consumption

North Enduse Code	*Htg/Clg Type*	*% of all Mobile homes*	*Htg/Clg Efficiency*	*Htg UEC kWh/yr*	*Clg UEC kWh/yr*
NMNE	ER / -	3%	100% / -	9603	0
NMNEC	ER / CAC	5%	100% / 9.96 SEER	9603	1307
NMNER	ER / RAC	6%	100% / 9.0 EER	9603	405
NMNHP	HP	0%	7.24 HSPF/ 9.86 SEER	4635	1244
NMNG	Gas-Other / -	36%	- / -	0	0
NMNGC	Gas-Other / CAC	24%	- / 9.96 SEER	0	1307
NMNGR	Gas-Other / RAC	27%	- / 9.0 EER	0	405
Total existing		101%			
South *Enduse Code*	*Htg/Clg Type*	*% of all Mobile homes*	*Htg/Clg Efficiency*	*Htg UEC kWh/yr*	*Clg UEC kWh/yr*
NMSE	ER / -	11%	100% / -	5161	0
NMSEC	ER / CAC	24%	100% / 9.96 SEER	5161	2716
NMSER	ER / RAC	19%	100% / 9.0 EER	5161	923
NMSHP	HP	2%	7.24 HSPF/ 9.86 SEER	2434	2740
NMSG	Gas-Other / -	14%	- / -	0	0
NMSGC	Gas-Other / CAC	15%	- / 9.96 SEER	0	2716
NMSGR	Gas-Other / RAC	15%	- / 9.0 EER	0	923
Total new		*100%*			

(1) Room air conditioner UEC is assumed to be 31% and 34% of corresponding CAC UEC in the north and south, respectively (from NERC regional utility data--RCG/Hagler-Bailly 1990).
(2) UECs were obtained from PEAR using a prototype one-story single family home with aluminum window sashes. The PEAR results for the north were adjusted from Cincinnati weather (the nearest city to Chicago with crawl space in the PEAR database) to Chicago weather using ratios of heating and cooling degree days. PEAR results in the south are based on Charleston, SC weather.
(3) Floor area is the national average for mobile homes sold in 1989, from MHI 1991b.
(4) Infiltration rates are estimates from Allen Lee of Battelle PNL (personal communication, April 1991) of existing mobile homes in the Pacific Northwest. Lee's ACH of 0.4 was adjusted by the specific infiltration rate for our northern and southern regions in order to account for the difference in weather between Seattle and Chicago (or Charleston). We assumed that our prototype homes and homes in Seattle have the same specific leakage area.
(5) All other shell characteristics were obtained from Manufactured Housing Institute estimates of the most popular shell packages sold in 1990 by region (MHI 1991a).
(6) The saturations of homes in each space conditioning category were for homes built 1980-88, from RECS 87.
(7) No shell measures are applied to mobile homes, only equipment efficiency measures.
(8) HP = heat pump; ER=electric resistance; CAC/RAC= central or room air conditioners
(9) Furnace fan electricity use for non-electric furnaces is counted as "miscellaneous energy" and does not appear in this table.
(10) Equipment efficiencies are from LBL REM (1991) for 1990 new units, based on extrapolation from 1987 ARI data.

Non-space conditioning end uses

Table 12 shows baseline saturations in 1990 and 2010, and the UECs for average appliances existing in 1990, and for the typical new appliance being installed in 1990.

Water heating: The UEC for electric water heaters reflects the 1990 standards, and includes the hot water used in dishwashers and clotheswashers. Energy savings from hot water reductions from the 1994 efficiency standards on laundry products are included as measures in the supply curve.

Refrigerators and Freezers: The top-mount auto-defrost refrigerator comprises about 2/3 of all refrigerators sold in the U.S. (LBL REM 1991), and this model is the one chosen to represent the conservation potential for all refrigerators. Freezers are assumed to be half upright manual defrost and half chest manual defrost. The frozen efficiency baseline includes the 1990 standards, but not the updated 1993 standards for these products (which are included as measures on the supply curve).

Lighting: The lighting end use includes both interior and exterior lighting. The baseline assumes all incandescent lighting with no controls. Saturations are an average from from the Residential Appliance Saturation Surveys (RASSs) from eight utilities. Energy consumption is estimated for a weighted-average of 4 house types from RECS (US DOE 1989a) housing stock: large single family, medium single family, small single family/mobile homes, and apartments. See Appendices 3 and 6 for more details.

Other: The Other end-use is comprised of various categories, such as TVs, electric ranges, clothes dryers, and Miscellaneous. The Miscellaneous category includes all electricity use that has not been disaggregated into an end-use. Only furnace fans, clotheswasher and dishwasher motors, and various other motors were distinguished within Miscellaneous. The rest of miscellaneous is not well specified, and more work is needed in this area (Rainer et al. 1990).

Baseline electricity use

Figures 3 and 4 show the breakdown of 1990 and 2010 U.S. residential electricity use, by end-use, based on the results of the supply curve model. Appendix 4 contains more detail on frozen efficiency end-use energy from ACCESS, and **Table 13** compares the LBL REM frozen efficiency forecast to that from ACCESS. Agreement is within 7.1% for total residential electricity consumption. This difference is caused principally by the base-year difference in space conditioning energy. The representation of space conditioning in LBL REM is not currently as detailed as that in the supply curve program, so the 13% difference between the forecasted baselines in 2010 is not a grave concern. As ACCESS's inputs become more closely integrated with those of LBL REM, we expect these differences to be reduced.

D. Conservation Measures

Once the baseline forecast has been established, the next step is to estimate the costs and energy savings for measures that reduce the baseline energy consumption.

Costs of measures

Space conditioning shell measures: Costs of space conditioning energy conservation measures are taken from Koomey et al (1991) for new single-family buildings and Boghosian (1991) for existing single-family buildings. In both cases, the costs were averaged for the north and south regions, weighted by the average number of households

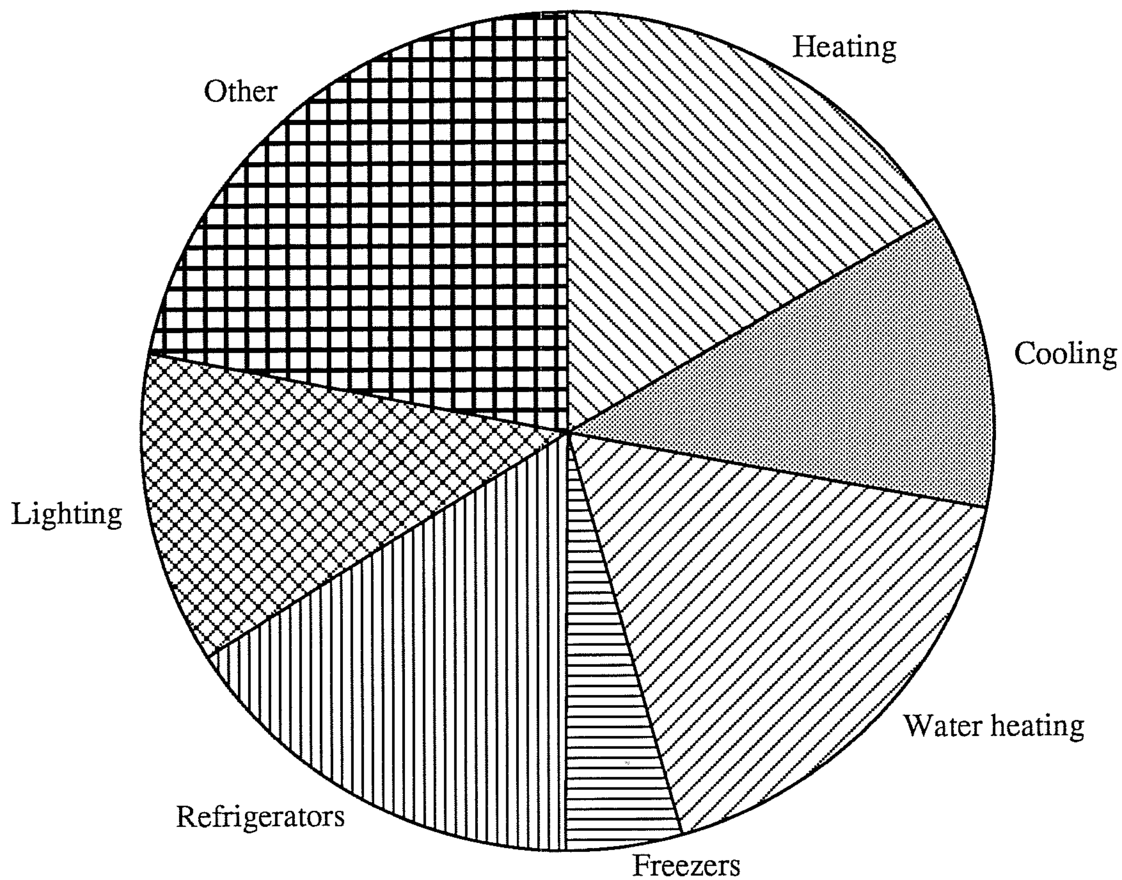
Table 12: Baseline saturations and unit energy consumption of non-space-conditioning appliances				
Appliance	*Average saturation of appliances existing in 1990*	*Average saturation of appliances in 2010*	*Average UEC of appliances existing in 1990*	*Average UEC of new appliances in 1990*
Black and white television sets, 13 inch (1)	37.0%	37.0%	50	50
Clothes Dryer electric	53.8%	59.4%	904	880
Color television sets 19-20 inch (1)	93.0%	92.0%	205	205
Elec. Water Heater	40.2%	44.5%	3850	3539
Electric Range	65.3%	75.2%	1010	944
Lighting (Indoor and Outdoor)	100.0%	100.0%	1060	1060
Freezer	35.7%	30.6%	1104	568
Miscellaneous electricity	100.0%	100.0%	559	559
Refrigerator	114.0%	115.6%	1226	893

(1) TV saturations are a weighted average of 31 national utilities' data and represent customer saturation, not appliance saturation. Customer saturation is the fraction of households having at least one appliance; appliance saturation reflects the number of appliances in each house and can therefore be greater than 100%. However, usage patterns of second and third TV sets are not well documented and we have ignored these additional units.

(2) All other appliance saturations are national averages from LBL REM (1991).

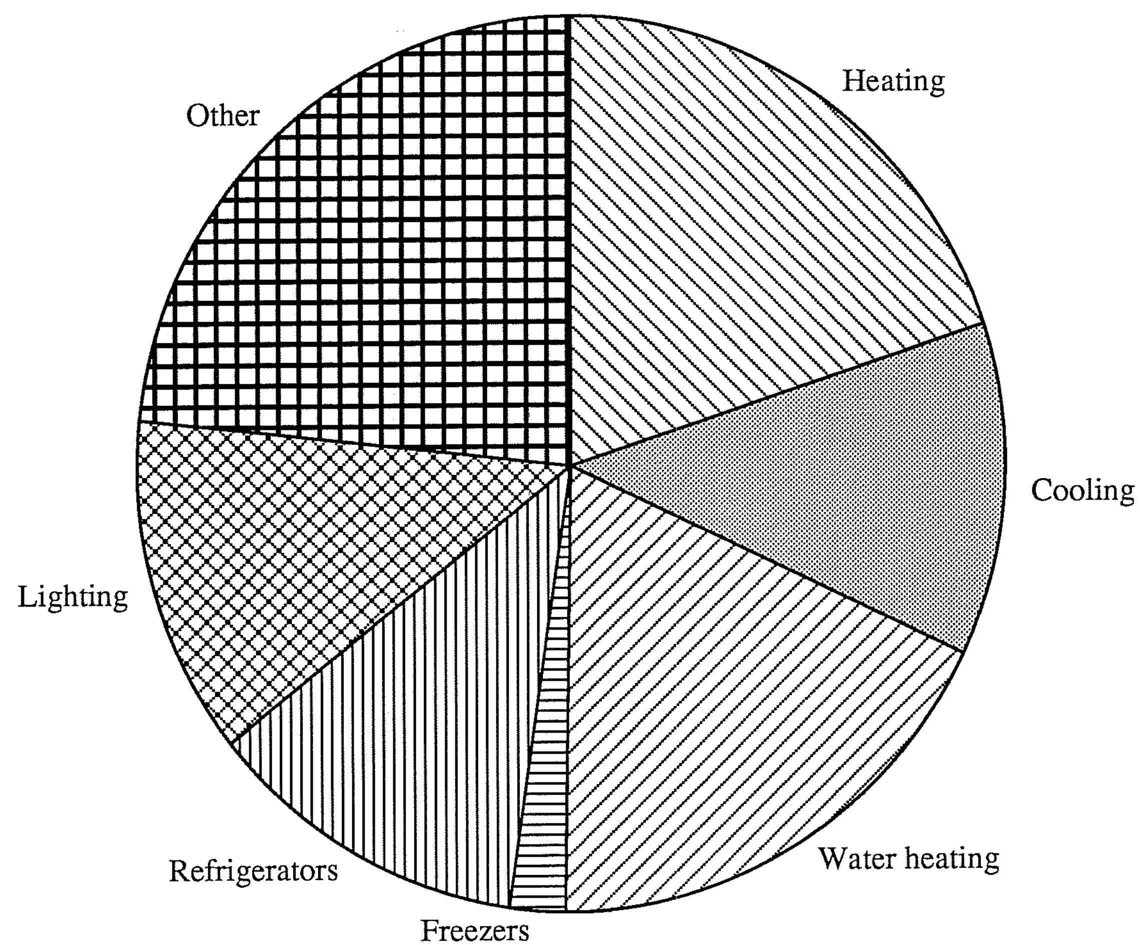
(3) UECs from LBL REM (1991), except for TVs (from US DOE 1988) and lighting (see Appendix 3 and Appendix 6 for details). UECs for new appliances reflect the 1990 standards (where applicable). Refrigerators and freezer UECs may not exactly match the LBL-REM weighted average over all units sold, as we have for these two end-uses represented all possible units sold with one or a two prototypes (see Appendix 3 for details). In these two cases, the prototype UECs are directly taken from LBL-REM (1991).

Figure 3: U.S. Residential Electricity Use 1990



Frozen efficiency baseline in 1990 = 828 TWh
Source: ACCESS (see Table 13 and Appendix 4)

Figure 4: U.S. Residential Electricity Use 2010 (Frozen Efficiency Baseline)



Frozen efficiency baseline in 2010 = 1008 TWh
Source: ACCESS (see Table 13 and Appendix 4)

Table 13: Comparison of ACCESS and LBL Residential Energy Model frozen efficiency forecasts

	1990 ACCESS TWh	*1990 LBL REM TWh*	*1990 ACCESS/ LBL REM*	*2010 ACCESS TWh*	*2010 LBL REM TWh*	*2010 ACCESS/ LBL REM*
Space conditioning	232	253	*91.8%*	322	371	*86.9%*
Heating	137	149		201	231	
Cooling	95	104		121	140	
Water heating	146	146	*99.9%*	185	185	*100.2%*
Freezers	37	37	*100.5%*	21	21	*98.6%*
Refrigerators	132	132	*100.0%*	121	126	*95.8%*
Lighting	100	104	*96.5%*	124	132	*93.9%*
Other	181	181	*100.1%*	234	249	*93.9%*
Total	828	852	*97.2%*	1008	1085	*92.9%*

(1) The supply curve program (ACCESS) calculates space conditioning energy but does not separate it into heating and cooling. In this table, the relative amounts of heating and cooling from LBL REM (1991) are used to separate the supply curve's space conditioning energy into heating and cooling energy.

or by 1987 housing starts for existing and new buildings, respectively. See Appendices 2 and 3 for costs by measure.

Boghosian's documentation presents *total costs* (in million dollars) and *total savings* (in TWh) for efficiency measures in all existing homes, and does not present the cost or savings per measure per applicable home (Boghosian 1991). The costs and savings shown in Appendix 3 are averaged over all homes, since we could not easily derive the cost per measure per applicable home. *For this reason, the per unit measure costs and savings in Appendix 3 appear to be too low. These parameters are, however, correctly used to calculate the CCEs.*

The costs of window measures for existing buildings are based on the full cost of replacement, which assumes that the windows would not have been replaced anyway (Boghosian 1991). The long lifetime of windows makes this assumption roughly reasonable, though there is some window replacement that occurs as they break or as buildings are renovated. This assumption vastly overstates the CCE if windows are being replaced anyway, and this omission will be corrected in future work.

The costs of window improvements in new buildings are the incremental costs of improving efficiency beyond the prototype's base case assumption. Superwindows, which have an overall R-value (including frame effects) of R-5.5, are included for new buildings in the north. Spectrally selective glazings, which block the heating effects of ultraviolet and infrared radiation but do not affect visible transmissivity, are included for new homes in the south. Neither of these more advanced glazing technologies are included for existing buildings. This omission will be corrected in future updates to the supply curves.

Space conditioning equipment in multifamily buildings and mobile homes: The capital costs of space conditioning equipment in multifamily buildings and mobile homes have been adjusted using information from EPRI (1987) relating equipment capital costs to heating and cooling loads. We assume that each multifamily unit has its own space conditioning equipment. The 1987 RECS or Residential Energy Consumption Survey (US DOE 1989a) indicates that slightly more than 80% of all central air conditioners (CACs) in existing multifamily (MF) dwellings are individual units, and 94% of CACs in new MF units are individually owned (data for heat pumps are inconclusive due to small sample size). The assumption of all individual units makes the analysis conservative, since there are economies of scale in improving the efficiency of a single large unit instead of improving the efficiency of many small units. These homes usually have smaller loads per housing unit than the single-family homes upon which the absolute costs of equipment are based, and the costs of the equipment are adjusted accordingly.

Water heating: Water heating measures include savings from options affecting standby losses, conduction, and water flow rates, as well as hot water[8] savings from the 1994 standard on laundry products (clotheswashers and dishwashers). The baseline new water heater meets the 1990 standard. See Appendix 3 for more details.

The heat pump water heater (HPWH) is included in our technical potential analysis as an advanced option that is not available in large numbers until after 1995. The technology itself is currently available, and reliable, but early reliability problems and high initial costs have limited its use (Beckerman et al. 1990, EPRI 1984, Lerman 1988, Petrie and Peach

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[8]Motor savings from the Laundry product standards have been included as supply curve measures affecting the Other end use category.

1988). We assume that the Electric Power Research Institute's "third generation" HPWHs, which are now being tested, become commercially available by 1993.

HPWHs can have a large effect on space conditioning loads if they are located in the conditioned space (they will increase space heating loads and decrease space cooling loads). They also do not perform well in cold climates, except if placed in unheated basements that do not become too cold in winter. We have assumed that all homes in our southern region would be eligible for HPWHs (taking advantage of the reduction in cooling load), and only 10% of the homes in the north (i.e., those homes with unheated basements) would be so eligible.

It is when discussing logistic considerations for advanced technologies like the HPWH that the limitations of the frozen efficiency/technical potential methodology become most apparent. There will be constraints in scaling up production of HPWHs that are both physical and economic. Economic constraints should in principle not be considered in a technical potential estimate, but in this case they are inextricably intertwined with the physical constraints. Current production of HPWHs is around 2000 units per year, but discussions with one of the larger manufacturers of these devices indicates that production could be increased to hundreds of thousands of units per year in a year or two, given sufficient demand (Shuford 1991).

We attempt to approximate the physical constraints in scaling up HPWH production by assuming that only half of eligible electric water heaters (EWHs) sold in the 1995-2000 period (that are not switched to natural gas) are converted to heat pumps. During the period 1995-2000, 50% of electric water heaters sold in the South (after fuel switching is accounted for) are converted to HPWHs, and 5% of EWHs sold in the North are converted to HPWHs. After 2000, we assume that all eligible EWHs sold during this period are converted to HPWHs.

The purchase cost of HPWHs would decrease if production were increased by a substantial amount, due to economies of scale (Chan 1991). For refrigerators, the rule of thumb is that consumer cost will decrease by about 10% if production of a particular model is doubled. For fluorescent ballasts, consumer cost will decrease 20-30% if manufacturing output is increased by a factor of ten.[9] Since the number of HPWHs sold in our technical potential case increases by a factor of 500 to 1000 over current levels, it is plausible to argue that consumer costs will decrease by at least 20% compared to current prices. We chose to reduce consumer cost by 20% as a conservative estimate.

Energy savings from HPWHs vary from 30% to 70%, with more recent higher efficiency models tending towards the higher savings number. EPRI (1984) reviewed 45 utility field tests of savings from HPWHs in all regions of the U.S., and found that savings averaged roughly 50%. The EPRI third generation HPWHs are expected to save 60-65%, but we assumed 50% savings to be conservative. See Appendix 3 for details on costs and energy savings.

Refrigerators and Freezers: Costs for efficiency improvements in refrigeration equipment have been calculated assuming that chlorofluorocarbon (CFC) refrigerants and

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[9]Refrigerators are much more similar to HPWHs than are ballasts, but the large increase in production that we forecast (by factors of 500 to 1000) make our 20% cost reduction conservative. Shuford (1991) estimates that such a large production increase would reduce the capital cost of the third generation HPWHs to 50% of their cost at the time when the devices are first introduced in 1992 or 1993.

blowing agents *are unavailable* throughout the analysis period, using costs from US DOE (1988, 1989b).

Lighting: Costs of lighting equipment are shown in Appendix 6, and are taken from Grainger (1990), Real Goods (1990) and EFI (1990).

Laundry products: Costs for efficiency improvements of clothes washers, clothes dryers, and dishwashers are taken from US DOE (1990b). The CCEs for shifting to horizontal axis clothes washers depend on whether heat pump water heaters are assumed to be implemented first (there are separate measures for each of the possible cases).

Heat pump (HP) dryers are assumed to saturate the electric dryer market after the year 2000. Prototypes of both HP dryers and microwave dryers have been tested successfully, but most development work is currently being devoted to microwave dryers. HP dryers save more energy and have a lower CCE than microwave dryers, so we chose them for our technical potential case. Changes in current research and development funding would have to occur for HP dryers to become commercial, which is why the measure is delayed until the year 2000.

Other Non space-conditioning end-uses: Costs of other non space-conditioning energy conservation measures are taken from LBL (1990), LBL REM (1991), McMahon (1986), US DOE (1988, 1989b, 1990b), Perlman (1987), and Goldstein et al. (1990), and from other references listed in Appendix 3. For costs by measure see Appendix 2.

Fuel switching measures: The CCEs for gas fuel-switching measures include the present-valued cost of the natural gas used to run the appliance, using the gas price projections in the Reference case from the U.S. Department of Energy's Annual Energy Outlook (US DOE 1990a). This approach was adopted because the cost of delivering service equivalent to an electric appliance includes both the capital cost of switching and the cost for non-electric fuel.

Fuel switching from electricity to direct use of natural gas results in an increase in gas use. **Table 14** shows this increased use, along with the measure codes, CCEs,the number of units switched, and the electricity savings for each appliance. The total increase in gas use if all three of these fuel switching measures are fully implemented is about 5% of the US DOE's estimate of *residential* natural gas use in 2010 (4.7 Quadrillion Btus, from US DOE (1991)).

Appliances are only switched in homes that have gas hookups in the home already, but have an *electric* water heater, clothes dryer, or range (based on the saturations contained in the Residential Appliance Saturation Surveys for the utilities shown in Appendix 9). No switching of electric space heating to gas was included, because almost all houses with gas service already have gas space heat. Further fuel switching (including switching electric furnaces to gas) may be possible in areas to which gas lines could be inexpensively extended. Assessing this potential would require significant additional analysis, but the large electricity savings possible in each house (see Tables 6 to 11) make this option worthy of further study.

Table 14: Electricity savings, increased gas use, and cost of fuel switching to natural gas

	Units	*Electric range to gas range*	*Electric water heater to gas WH*	*Electric dryer to gas dryer*
Measure code		ERNG02	EWH08	CD-E03
Cost of conserved energy	¢/kWh	6.2	4.7	6.1
Applicable fraction	%	22%	8.5%	36%
Per unit natural gas use	therms/unit/yr	47.7	159.5	34.9
Units switched by 2010	millions	19.4	4.7	25.0
Total additional gas use (in 2010)	TBtus/yr	93	75	87
Electricity savings	kWh/unit/yr	944	3539	807
Total electricity savings (in 2010)	TWh/yr	18	17	20

(1) Cost of conserved energy includes the present-valued cost of the natural gas use assuming the residential gas price forecast in US DOE 1990a, levelized using a 7% real discount rate.
(2) Applicable fraction calculated using data from residential appliance saturation surveys from utilities listed in Appendix 9. It represents the fraction of all electric appliances purchased in a given year that can be switched to natural gas.
(3) Per unit gas use from LBL REM (1991).

Energy savings

For space conditioning in new and existing single-family buildings, energy savings for specific measures are calculated using the batch version of PEAR and Chicago or Charleston weather sites (see Appendix 8 for details on the space conditioning analysis). The exceptions to this rule are the estimates of energy saved from "superwindows" and from spectrally-selective glazings, which are calculated using a beta-test version of an LBL model (RESFEN 1.0) for estimating heating and cooling energy use associated with various window technologies (Sullivan 1991). Interactions between space conditioning equipment efficiency and shell measures are correctly accounted for. See Appendix 3 for details.

Energy savings for *appliances and space conditioning equipment* in multifamily buildings and mobile homes have been included in our analysis. Unfortunately, there was insufficient data to model space conditioning energy savings *from shell measures* in these buildings. Some measured data on energy savings from retrofits of fuel-heated multifamily buildings were available (Cohen et al. 1991, Goldman et al. 1988), but data on electrically heated buildings are largely confined to the Northwestern U.S. (in a climate quite different than that of the U.S. average). NPPC (NPPC 1986, NPPC 1989) has estimated the conservation potential for multi-family buildings in the Northwest, but no comparable analysis exists for the U.S. Judkoff (1991, 1990) and Baylon et al. (1990) have analyzed savings for mobile homes for particular regions of the country, but not for the U.S. as a whole.

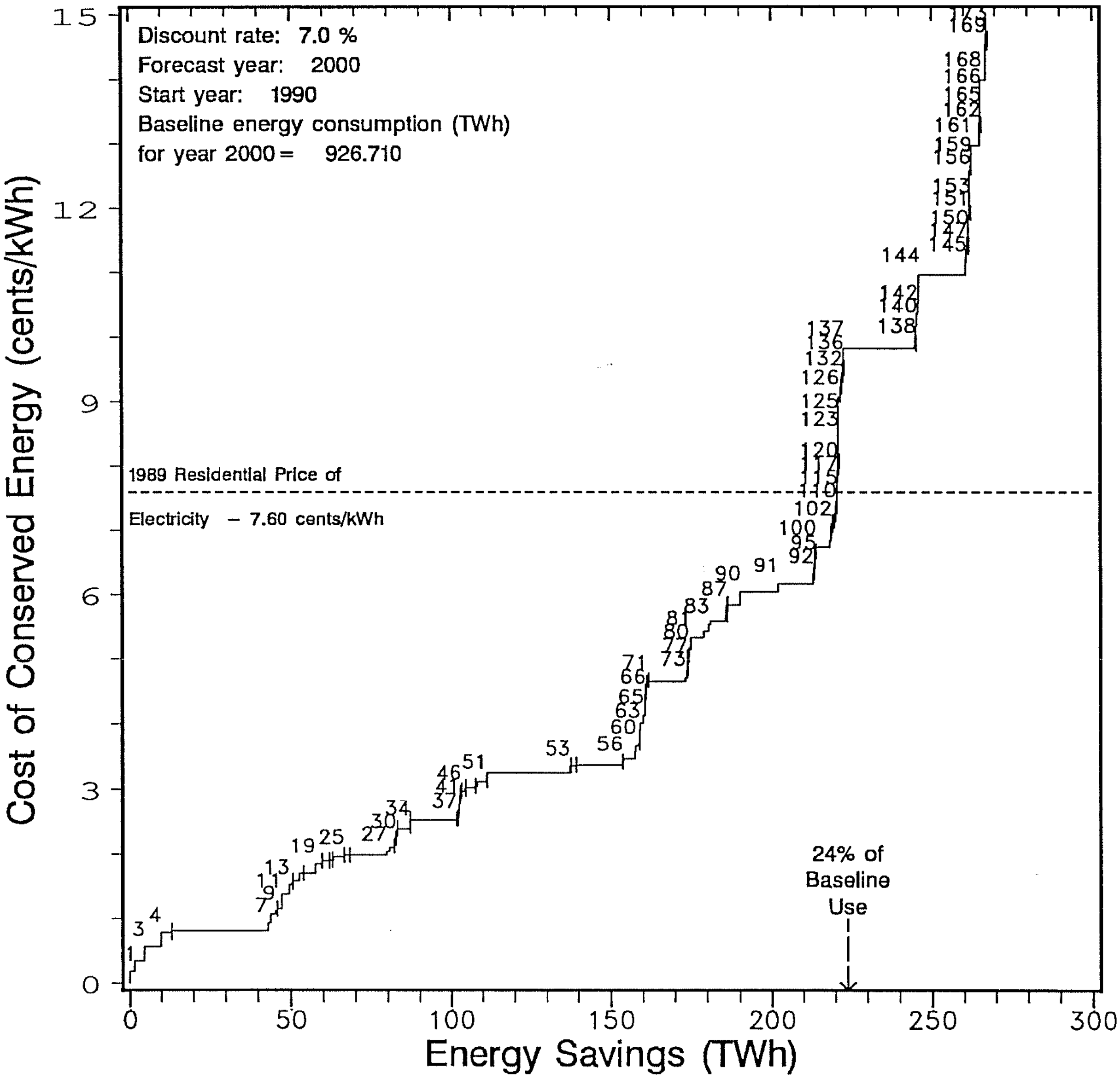
Multifamily space conditioning electricity comprises about 7% of the frozen efficiency baseline in 2010, and mobile home space conditioning electricity comprises about 2% of this baseline. To the extent that additional energy savings could be achieved using MF and mobile home space conditioning shell measures, the savings from our analysis are conservative. Savings from shell measures comparable to those found in single-family homes (roughly 10-15% of the SF frozen efficiency baseline at a cost of less than 7.6¢/kWh) would yield an additional 10 to 15 TWh of energy savings from MF and MH space conditioning shell measures.

Energy savings for appliances were taken from our national database (see LBL (1990) and Appendix 3 for more details). No attempt was made to correct for changes in space conditioning loads due to changes in the energy use of non-space conditioning appliances located in the conditioned space.

III. RESULTS

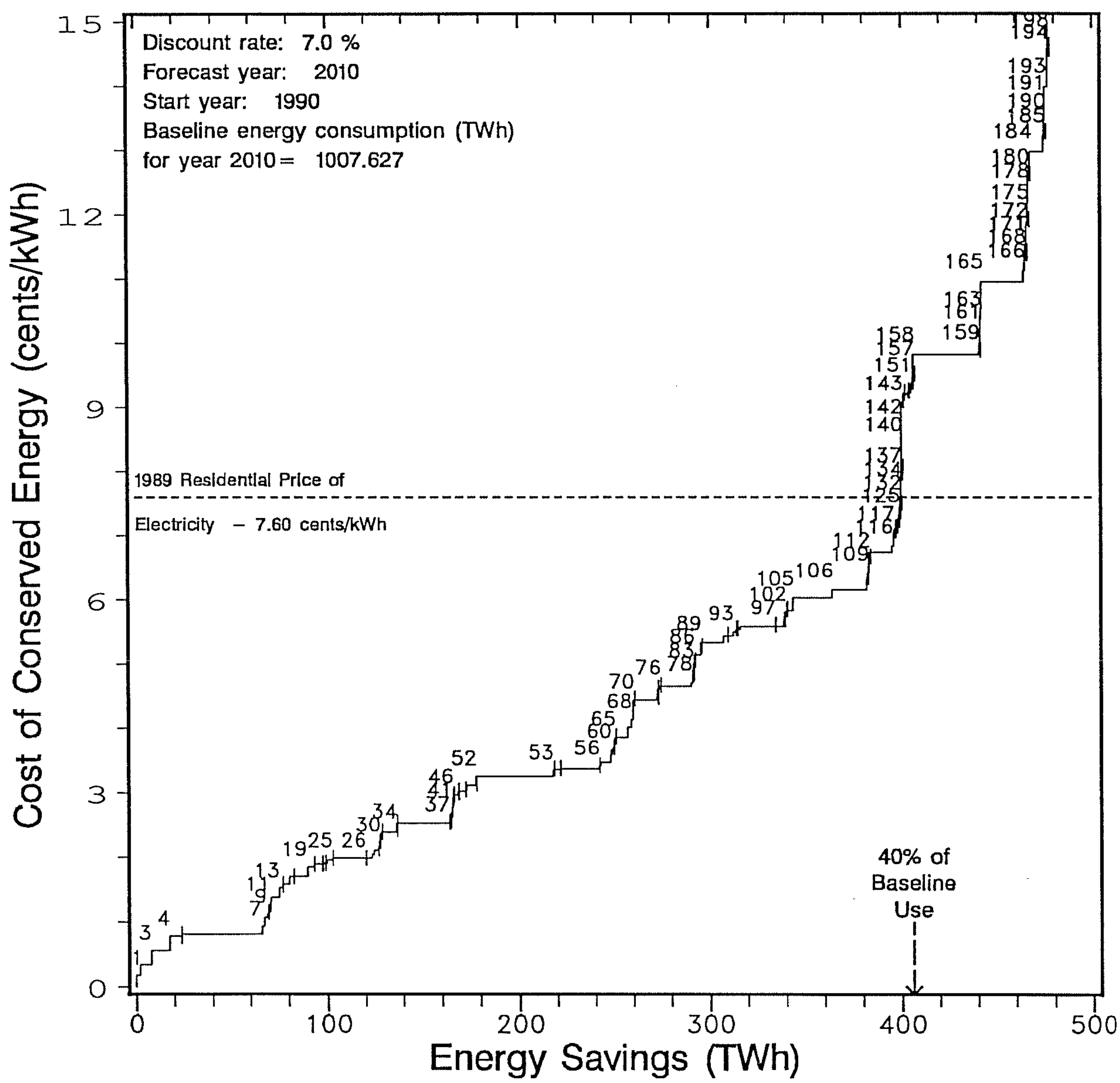
Figure 5 shows a supply curve of conserved energy for the U.S. residential sector in 2000, and **Figure 6** shows the supply curve for 2010. Appendices 2a and 2b contain details on the measures that make up the supply curve in these two years. The total technical potential in 2010 (without considering cost) is about 486 TWh, or about 48% of the frozen efficiency baseline. The technical potential in 2000 and 2010 for energy savings costing less than 7.6¢/kWh is about 24% and 41% of each year's baseline use, respectively. The potential corresponds to 250 TWh in 2000 and 404 TWh in 2010,

Figure 5: Maximum Technical Potential in 2000



A supply curve of conserved electricity for the United States residential sector. Each step represents a conservation measure (or a package of measures). The width of the step indicates the nationwide electricity savings from the measure and the height of the measure indicates the cost of conserved electricity. The end uses include space conditioning, water heating, refrigeration, lighting, and miscellaneous.

Figure 6: Maximum Technical Potential in 2010



A supply curve of conserved electricity for the United States residential sector. Each step represents a conservation measure (or a package of measures). The width of the step indicates the nationwide electricity savings from the measure and the height of the measure indicates the cost of conserved electricity. The end uses include space conditioning, water heating, refrigeration, lighting, and miscellaneous.

implying a technical potential for energy savings of 70-75 baseload 1000 MW power plants by 2010.[10]

Figure 7 indicates that electric water heating measures offer the largest potential savings (in absolute terms) for costs less than 7.6¢/kWh of any single end use (slightly more than 110 TWh, of which about 17 TWh, or roughly 15%, is attributable to fuel switching to natural gas). Space conditioning measures are next most important in absolute terms, saving about 100 TWh. Lighting measures save about 60 TWh, as do refrigerator and freezer measures together. In percentage terms (relative to each end-use category's baseline usage), water heating savings potential is the greatest (60%), followed by lighting (47%), refrigerators (39%), and space conditioning (31%).

Table 15 presents a summary of residential electricity use and savings.by geographic region. The number of households in the Southern region is projected to grow more quickly than in the Northern region, but the total number of households in 2010 is still larger in the North than in the South. Total electricity use is slightly larger in the North in both 1990 and 2010, but *space conditioning* electricity use is split almost exactly equally between the two regions in 1990 and is slightly larger in the South by 2010. Total electricity *savings* costing less than 7.6¢/kWh are slightly larger in the South, while space conditioning savings are larger by a factor of 1.7 to 1. This substantial difference is caused by the larger number of new homes in the South (because efficiency improvements are cheaper in new homes), the cost effectiveness of spectrally selective glazings, and the prevalence of air conditioning in the South.

Table 16 displays a breakdown of the energy savings and costs of appliance standards implemented 1992-1994. Annual expected savings from these standards in 2010 are roughly 47 TWh/year, or about 5% of the frozen efficiency baseline. Of the 410 TWh of technical potential savings costing less than 7.6¢/kWh, about 12% (or five percent relative to the frozen efficiency baseline) are accounted for by the post-1990 standards.

IV. IMPROVEMENTS TO THE ANALYSIS: FUTURE WORK

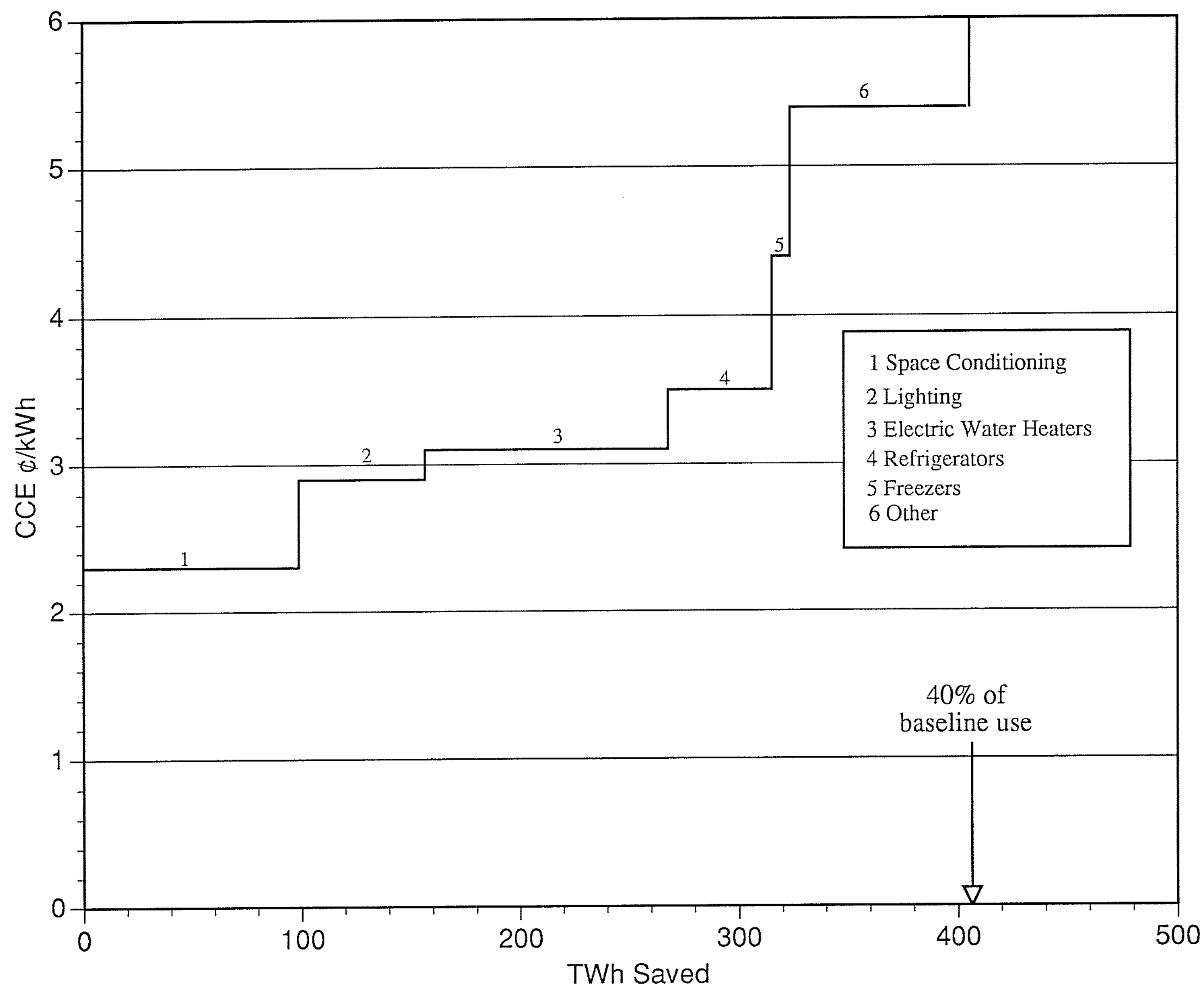
In creating the database of conservation measures, we frequently were forced to make compromises because of data limitations, weaknesses in computer tools, or resource constraints. On balance, we believe that correcting for data omissions and methodological limitations would *increase* the energy savings and *decrease* the cost of conserved energy, so in that sense our analysis is conservative. This section describes some of the limitations of this analysis, and presents our "wish list" for improving the conservation supply curves. As we continue to update the supply curves on a regular basis, many of these limitations will be corrected.

A. Multifamily and mobile home building-shell-related energy savings

The frozen efficiency baseline includes space conditioning energy use in multifamily buildings and mobile homes. We do not include building shell measures for these end-uses, because of an inability to easily simulate mobile home and multifamily building space conditioning energy use, and uncertainty about the costs of improving

[10]This crude comparison is presented here only to establish the order of magnitude. More accurate calculations would account for the time at which conservation measures save energy relative to the utility system peak demand, and relate these "load shape characteristics" to baseload, intermediate and peaking supply resources. See Koomey et al 1990 for more details.

Figure 7: Energy Savings and Costs by End-Use in 2010



Each segment of this curve shows the total electricity savings and the average cost of conserved energy for all measures in Figure 5 that cost less than 7.6¢/kWh (grouped by end use).

Table 15: Residential electricity use and savings potential by geographic region			
	North	South	Total
Number of Households 1990 (millions)	53.3	40.7	94.0
Percentage of Total	*56.7%*	*43.3%*	*100%*
Number of Households 2010 (millions)	64.0	53.9	117.9
Percentage of Total	*54.3%*	*45.7%*	*100%*
TOTAL RESIDENTIAL ELECTRICITY CONSUMPTION			
Total 1990 (TWh)*	455	373	828
Percentage of Total	*55.0%*	*45.0%*	*100%*
Total Frozen Efficiency Baseline Electricity Use 2010 (TWh)*	529	479	1008
Percentage of Total	*52.5%*	*47.5%*	*100%*
Total Savings Potential in 2010 for CCE ≤ 7.6 ¢/kWh (TWh) **	190	214	404
Percentage of Total Savings Potential	*47.1%*	*52.9%*	*100%*
Energy Savings Potential as a Percentage of Total Frozen Efficiency Energy Use in 2010	35.9%	44.6%	40.1%
SPACE CONDITIONING ELECTRICITY CONSUMPTION			
Total Space Conditioning (SC) 1990 (TWh)	117	115	232
Percentage of Total SC Use	*50.6%*	*49.4%*	*100%*
Total Space Conditioning Electricity Use Frozen Efficiency Baseline 2010 (TWh)	157	166	322
Percentage of Total SC Use	*48.6%*	*51.4%*	*100%*
Space Conditioning Savings Potential in 2010 for CCE ≤ 7.6 ¢/kWh (TWh)	36.6	62.1	98.7
Percentage of Total Savings Potential	*37.1%*	*62.9%*	*100%*
Space Conditioning Savings Potential as a Percentage of Total Frozen Efficiency Space Conditioning Energy Use in 2010	23.4%	37.5%	30.6%

(1) All non-space-conditioning electricity use is assumed to be proportional to the number of households in the Northern and Southern regions.

(2) Five-sixths of the electricity savings from heat pump water heaters accrue in the South, and 1/6 in the North (see text and Appendix 3 for explanation). Otherwise, all non-space-conditioning energy savings are assumed to be proportional to the number of households in the Northern and Southern regions.

Table 16: Savings in 2010 from post-1990 appliance efficiency standards affecting electric end-uses

Appliance	House Type	Year of Standard	Cost of Conserved Energy ¢/kWh	Savings in 2010 TWh/yr	Savings in 2010 % of 2010 baseline
Central Air Conditioner (CAC)	SF	1992	5.6	1.96	0.2%
	MF	1992	8.7	0.37	0.0%
	MH	1992	5.0	0.25	0.0%
	All	*1992*	*6.0*	*2.58*	0.3%
Heat Pump (HP)	SF	1992	2.6	2.64	0.3%
	MF	1992	4.0	0.34	0.0%
	MH	1992	2.8	0.02	0.0%
	All	*1992*	*2.8*	*3.01*	0.3%
Refrigerator	*All*	*1993*	*2.4*	*27.52*	2.7%
Freezer	*All*	*1993*	*3.4*	*3.42*	0.3%
Clothes dryer	*All*	*1994*	*3.1*	*5.08*	0.5%
Clothes washer	*All*	*1994*	*2.1*	*3.39*	0.3%
Dishwasher	*All*	*1994*	*0.2*	*2.14*	0.2%
Total from Standards				47.14	4.7%
Total less than 7.6¢/kWh				46.39	4.6%

(1) CAC and HP savings calculated using prototypes defined in Table 5.
(2) Electricity savings costing less than 7.6¢/kWh in the supply curves in Figures 5 and 6 include the roughly 47 TWh savings from appliance standards.
(3) Standards for CACs/HPs are assumed to be the first measure in all shell packages for housetypes with this equipment (for purposes of calculating energy consumption). They are ranked in the supply curve by CCE, and do not always come in below 7.6¢/kWh. However, 98% of the savings cost less than 7.6¢/kWh.
(3) In single-family homes, we switch all CACs w/electric furnaces to HPs. Savings from the standards for the CACs in single-family homes that are switched to HPs are not included in the savings in this Table. Similarly, savings from the HP standards for the switched CAC units were not included (the CACs are switched directly to the most cost-effective HP).
These 'lost' savings are on the order of 0.5 TWh in 2010.

existing mobile home thermal integrity. Savings from improvements in space conditioning equipment *are* included for these end-uses.

Some research has been done on this topic, which should be extended to the national level. Space conditioning energy savings in existing mobile homes have been estimated for Colorado weather from Judkoff (1991, 1990). Savings in new mobile homes have been estimated for the Northwest by Baylon et al. (1990). Multifamily costs and energy savings have been estimated by the Northwest Power Planning Council (NPPC 1986, NPPC 1989), while space conditioning loads for prototypes all over the U.S. have been estimated by Ritschard and Huang (1989).

B. Shell measures for existing and new homes

Existing single-family buildings: Advanced window options (such as superwindows and spectrally-selective glazing) have not been included for these buildings, and they should be. Costs of window replacement should be calculated for two cases: (1) assuming that the window would be replaced anyway, and estimating the incremental cost of upgrading the window, and (2) assuming that the window would not be replaced anyway. Estimates of the natural retrofit rate (i.e. because of breakage or window age) are currently being obtained from window and renovation trade associations.

New single-family buildings: all wall insulation levels higher than R-19 are assumed in our analysis to be reached using exterior sheathing, which is relatively expensive. Mass--producible advanced wall technologies for new buildings, including I-beam construction (used in Sweden--(Andrews 1990b, Schipper et al. 1985)), steel frame construction (Johnson and Liebeler 1991), foam blocks (Gilmore 1987), or solid-core foam walls may reduce the costs of achieving higher insulation values in walls.

Advances in windows are proceeding at a pace more characteristic of the computer industry than the generally more sedate building industry. Cheaper coatings and noble gas fillings are becoming the norm, and the goal of producing a window that would yield a net heat gain facing any direction on any northern U.S. house (R-8, including frame effects) is now within reach (Bakke 1990, Feder 1990, Gilmore 1986, Jones 1990, Warner 1990). New technologies on the horizon include chromogenic glazings that allow electronic control of window transmissivity (Moore 1987, Selkowitz and Lampert 1989) and innovative heat recovery schemes using controlled window infiltration (Pop Sci 1989).

Ventilation with heat recovery (which replaces uncontrolled infiltration as a means of preserving indoor air quality) is a technology that has matured in the past decade and is used widely in the Northwest (Lubliner and Young 1990). It has not been included in our conservation potential estimates. Both whole-house and room units are available (Cons. Rpts. 1985). Use of a tightly sealed shell with mechanical ventilation can achieve substantial further reductions in heating load due to infiltration, at a small cost in additional energy to operate the ventilation (Feustel et al. 1987).[11] Early results with these devices were mixed (Fisk and Turiel 1983, Turiel et al. 1983), but further experience has proved their reliability.

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[11] Ventilation with heat recovery may also help to achieve capital cost savings in the heating system--see section IV. C

C. Capital cost savings for advanced shell measures

Substantial improvements in shell efficiency can result in capital cost savings for space conditioning equipment. In the limiting case for space heating, the furnace can be eliminated altogether, and replaced with a larger water heater, as has been done by Bigelow Homes near Chicago (Andrews 1990a, Donovan 1988). Assessing these potential capital cost savings requires a whole-system analysis approach much more complicated than the one used in this study. EPRI (1987) has taken the first steps towards systematizing such an analysis.

D. Window orientation/passive solar features/landscaping

Few data exist about window orientation in new homes, but simple calculations suggest that using shading (awnings, trellises, shade screens, thermal curtains, or overhangs) and allocating more windows to the south and west side of northern houses (and more to the northern side of houses in the south) can reap substantial energy savings benefits. In the absence of data, our analysis assumed that window area is spread equally on all four walls, and that there are overhangs on all windows.

No other passive solar options are considered here, in spite of the potential energy savings available from these options (Kahn 1991), because costs for these improvements are more difficult to estimate than for simple changes in insulation levels. Both energy savings and costs of passive solar buildings are dependent on the complete building design and not just on the characteristics of the components.

Many analyses suggest that landscaping can have major effects on energy use (Huang et al. 1990, Meier 1991), but little information is available on the applicability of such measures to new and existing homes. Data are needed on the number of trees now planted around houses, the kind of trees typically planted, and the window orientation. More research is needed on these issues to assess the potential for reducing energy use using landscaping.

E. Internal loads

Changes in space conditioning loads due to improvements in appliance efficiency are not included in the supply curve analysis. In general, improvements in appliance efficiency will increase heating loads and decrease cooling loads. The LBL residential energy model (LBL REM) does keep track of these interactions, and as LBL REM and the supply curve model become more closely integrated, we expect to include these effects. The importance of heat pump water heaters and dryers in the technical potential case make a detailed assessment of the effects of internal loads imperative.

F. Infiltration

The data on baseline infiltration in both new and existing buildings of all types are based on small sample sizes that are heavily weighted towards buildings in California and the Northwest (CEC 1990, Kolb and Baylon 1989, Modera 1986, Sherman et al. 1984). Many local government agencies and non-profit organizations perform pressurization tests using blower doors to measure infiltration rates and perform retrofits of houses in their region. These data have never been compiled in a systematic format for the U.S. as a whole, but such a compilation is urgently needed for national-level policy analyses. Measuring *savings* from specific infiltration reduction measures are also needed, because the available measured data are scanty and inconclusive (Butterfield 1989, Schlegel 1990).

G. Duct leakage

Duct leakage, which can be substantial in centrally-conditioned homes (Brook 1991), has not been included in the analysis. Modera's (1991) latest unpublished results on the effect of duct leakage on furnace and central air conditioning efficiency indicate that the nominal efficiency of furnaces should be multiplied by a factor of 0.65 to calculate actual efficiency of heat delivery, while the comparable number for cooling is 0.66. This huge correction factor indicates that the importance of duct leakage has traditionally been underestimated in conservation potential analyses. We will include this correction factor in future updates of the supply curves whenever Modera's detailed work is published. RECS (US DOE 1989a) indicates that 70-80% of all existing U.S. houses have ducts, so this issue is potentially an important one. Omitting this factor represents a conservatism, in the face of uncertainty about current data and about the effects of recent changes in duct sealing practice.

H. Long-term fuel switching to homes near gas supply

We consider fuel switching in homes that already have gas service, but do not assess the potential for extending gas mains into areas that are close to the existing distribution system, or for ensuring that as many new developments as possible have gas service. In the long-term, such fuel switching could in many cases be cost effective, especially where electric space heating and water heating are switched to gas simultaneously. A more comprehensive study is needed to assess the size and cost-effectiveness of this additional fuel-switching potential.

I. Integrated appliances and advanced appliances

No attempt has been made to include the potential energy savings from integrated appliances that combine the functions of space conditioning and water heating, or those of televisions and video cassette recorders.

Ground-source heat pumps, which are extremely efficient compared to air-source models, have not been included in our technical potential estimates. Solar water heaters and solar pool heaters are not included, though these are cost effective in some applications. Gas-fired air conditioners are currently in use for commercial applications, and may yield additional cost-effective fuel switching potential in residential space conditioning by the mid-1990s.

J. Treatment of appliance standards

Appliance standards implemented after 1990 (e.g. the 1993 refrigerator/freezer standards) have been treated in this study as having a positive cost to society (relative to the 1990 standard). This cost is used to rank the standard in the supply curve.[12] A *utility* considering programs to increase the efficiency of refrigerators would "receive" these energy savings at zero cost, even though the *customer* would have to pay something for them. Care must therefore be used in extrapolating these national results to specific utility service territories.

K. Lighting end-use

Lighting has been characterized in a relatively detailed fashion, considering that the available data are somewhat scanty. We expect some of these data to change as we

[12]These standards are always the first measures "implemented" regardless of CCE, even though the measures are shown on the grand supply curve ranked by CCE. This convention ensures that all energy savings for improving efficiency beyond the appliance standards are calculated correctly.

accumulate more information in conjunction with LBL's analysis of possible lighting efficiency standards. Technical improvements and cost reductions for compact fluorescent lamps, partly influenced by utility incentive programs, will be assessed in more detail.

L. Miscellaneous end-uses

More investigation is needed into the components of and the savings from the Miscellaneous end-use category. In particular, pool heaters, furnace fans for non-electric furnaces, computers, VCRs, and other high saturation electronic devices need more careful study.

M. Load shape characteristics

Once measured or calculated, load shape characteristics for each measure (as represented in simplest form by *conservation load factors* (Koomey et al. 1990) or in more comprehensive fashion by average monthly or weekly load shapes) could be included as fields in each record of ACCESS's database. This addition would improve the program's usefulness in least-cost utility planning analyses, because it would allow more accurate characterization of the coincident load savings attributable to the efficiency resources.

N. Additional data needs

Improved data are needed on the costs of switching to heat pumps (HPs) in existing homes with electric resistance (ER) heating and central air conditioner (CAC) cooling. We assumed that $600 would suffice to pay for retrofitting and reoptimizing the ventilation system, and that a standard HP would cost an additional $100 over the cost of a standard CAC. Since the lifetime of the CAC is 12 years and the lifetime of baseboard heaters is roughly twice that, we assumed that HPs would be installed at the rate of retirement of baseboard heaters, thus avoiding the costs associated with early retirement of equipment. Further research is needed to test the accuracy of these assumptions, although the measure is so cost effective that even a several-fold increase in capital cost would keep the CCE below 7.6¢/kWh in all cases.

Information on the costs of fuel switching for water heaters, ranges, and dryers is often anecdotal. These costs are site-specific, and we know little about the extent of constraints on fuel switching and on the cost penalties imposed by such constraints.

V. CONCLUSIONS

This analysis has demonstrated that there are significant, cost-effective energy efficiency resources available in the U.S. residential sector. The technical potential for energy savings in the U.S. residential sector by 2010 is roughly equivalent to 70-75 1000-MW power plants, at an average cost of conserved energy of 3.4¢/kWh (using only those efficiency resources costing less than 7.6¢/kWh). These savings represent about 40% of the frozen efficiency baseline. If conservation resources up to 14¢/kWh are considered, the total technical potential is about 48% of the frozen efficiency baseline. Potentially large efficiency resources have not been included in the analysis due to lack of data or lack of resources, including building shell improvements for mobile homes and multifamily buildings, expansion of the gas supply network, landscaping and passive solar techniques, and advanced space conditioning shell technologies for new homes.

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REFERENCES

Andersson, Brandt, William Carroll and Marlo R. Martin. 1986. "Aggregation of U.S. Population Centers Using Climate Parameters Related to Building Energy Use." *Journal of Climate and Applied Meteorology*. vol. 25, no. 5. p. 596.

Andrews, Steve. 1990a. "Building on Innovation". *JLC Midwest Edition*. January 1990. p. 32.

Andrews, Steve. 1990b. "Sweden's Super Houses". *Solar Age*. November 1985. p. 52.

Bakke, Timothy O. 1990. "Windows of Opportunity". *Popular Science*. May 1990. p. 108.

Baylon, David, Bob Davis, Mike Kennedy and Mike Lubliner. 1990. *Manufactured Homes Simulated Thermal Analysis and Cost Effectiveness Study*. Ecotope, Inc. and the Washington State Energy Office, for the Bonneville Power Administration. May 1990.

Beckerman, Richard, Lois Gordon and Vince Schueler. 1990. *Heat Pump Water Heaters: An Assessment of Current Technical and Economic Feasibility as a Demand-Side Resource in the Pacific Northwest*. The Washington State Energy Office, for the Bonneville Power Administration. November 1990.

Berry, Linda. 1989. *The Administrative Costs of Energy Conservation Programs*. Oak Ridge National Laboratory. ORNL/CON-294. November 1989.

Bodlund, Birgit, Evan Mills, Tomas Karlsson and Thomas B. Johansson. 1989. "The Challenge of Choices: Technology Options for the Swedish Electricity Sector." In *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications*. Edited by T. B. Johansson, B. Bodlund and R. H. WIlliams. Lund, Sweden: Lund University Press.

Boghosian, Stan. 1991. *Description of the Shell Thermal Characteristics of U.S. Residences and Calculation of Shell Retrofit Option Costs*. Lawrence Berkeley Laboratory. DRAFT LBL-29417. April 1991.

Brook, Dave. 1991. "Ductwork seen as major culprit in poor furnace performance". *Home Energy*. May/June 1991. p. 43.

Butterfield, Karen. 1989. "How Effective are Blower Doors?". *Home Energy*. January/February 1989. p. 25.

Carlsmith, Roger S, William U. Chandler, James E. McMahon and Danilo J. Santini. 1990. *Energy Efficiency: How Far Can We Go*? Oak Ridge National Laboratory. ORNL/TM-11441. January 1990.

CEC, California Energy Commission. 1990. *Occupancy Patterns & Energy Consumption in New California Houses (1984-1988)*. CEC. P400-90-009. September 1990.

Census, U.S. Bureau of the Census. 1990. *The Statistical Abstract of the United States 1990*. 110th Washington D.C.: U.S. Government Printing Office.

Chan, Terry. 1991. *Personal Communication:* "Discussion of economies of scale in appliance manufacturing, based on lessons from Appliance Standards Manufacturer impact analysis". LBL's Appliance Standards Group. June 1991.

Chernick, Paul and Emily Caverhill. 1989. *The Valuation of Externalities From Energy Production, Delivery, and Use: Fall 1989 Update*. A Report by PLC, Inc. to the Boston Gas Co. December 22, 1989.

Cohen, S. D., C. A. Goldman and J. P. Harris. 1991. *Measured Energy Savings and Economics of Retrofitting Existing Single-Family Homes: An Update of the BECA-B Database*. Lawrence Berkeley Laboratory. LBL-28147, volumes I and II. February 1991.

Cons. Rpts. 1985. "Heat-Recovery Ventilators". *Consumer Reports*. October 1985. p. 596.

Cummings, James B., John J. Tooley Jr, Neil Moyer and Rico Dunsmore. 1990. "Impacts of Duct Leakage on Infiltration Rates, Space Conditioning Energy Use, and Peak Electrical Demand in Florida Homes." In *Proceedings of the 1990 ACEEE Summer Study on Energy Efficiency in Buildings*. Asilomar, CA: American Council for an Energy Efficient Economy.

Donovan, Deborah. 1988. "Energy Efficiency Getting Simpler for Bigelow Co.". *Daily Herald*, Saturday, May 28, 1988.

EAP, Energy Analysis Program. 1987. *Program for Energy Analysis of Residences (PEAR 2.1): User's Manual*. Lawrence Berkeley Laboratory. PUB-610. March 1987.

EFI. 1990. *Energy Efficient Lighting: Prices/Order Form*. Energy Federation Inc., Framingham, MA. March 1990.

EPRI, Electric Power Research Institute. 1984. *Heat Pump Water Heaters*. EPRI. EM-3582, Project 2033-5. May 1984.

EPRI, Electric Power Research Institute. 1987. *TAG-Technical Assessment Guide: Vol. 2: Electricity End Use. Part 1: Residential Electricity Use--1987*. EPRI. EPRI P-4463-SR, vol.2, Part 1. September 1987.

EPRI, Electric Power Research Institute. 1990. *Efficient Electricity Use: Estimates of Maximum Energy Savings*. EPRI. CU-6746, Project 2788. March 1990.

Feder, Barnaby. 1990. "'Smart' Windows, Intriguing Potential". *New York Times*, Sunday, 8 April 1990, p. 11.

Feustel, Helmut E., Mark P. Modera and Arthur H. Rosenfeld. 1987. *Ventilation Strategies for Different Climates*. Lawrence Berkeley Laboratory. LBL-20364. March 1987.

Fisk, William J. and Isaac Turiel. 1983. "Residential Air-to-Air Heat Exchangers: Performance, Energy Savings, and Economics." *Energy and Buildings*. vol. 5, p. 197.

Geller, Howard, Anibal de Almeida, Barbara Barkovitch, Carl Blumstein, David Goldstein, Alan Meier, Peter Miller, Olivier de la Moriniere, Art Rosenfeld and Linda Schuck. 1986. *Residential Conservation Power Plant Study: Phase 1 - Technical Potential*. Pacific Gas and Electric Company. February 1986.

Gilmore, V. Elaine. 1986. "Superwindows". *Popular Science*. March 1986. p. 76.

Gilmore, V. Elaine. 1987. "Foam-Block House". *Popular Science*. December 1987. p. 52.

Goldman, Charles, Kathleen Greely and Jeffrey P. Harris. 1988. "Retrofit Experience in U.S. Multi-Family Buildings: Energy Savings, Costs, and Economics." *Energy*. vol. 13, no. 11. p. 797.

Goldstein, David, Robert Mowris, Bart Davis and Kari Dolan. 1990. *Initiating Least-Cost Energy Planning in California: Preliminary Methodology and Analysis*. Testimony Before the California Energy Resources Conservation and Development Commission (CEC). February 21, 1990.

Grainger. 1990. *General Catalog No. 377*. W. W. Grainger, Inc.

Hohmeyer, O. 1988. *Social Costs of Energy Consumption: External Effects of Electricity Generation in the Federal Republic of Germany*. Berlin: Springer-Verlag.

Huang, Y. Joe, Hashem Akbari and Heider Taha. 1990. *The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements*. Lawrence Berkeley Laboratory. LBL-24131. January 1990.

Hunn, Bruce D., Martin L. Baughman, Scott C. Silver, Arthur H. Rosenfeld and Hashem Akbari. 1986. *Technical Potential for Electrical Energy Conservation and Peak Demand Reduction in Texas Buildings*. Public Utility Commission of Texas. February 1986.

Johnson, Dean and Joanne Liebeler. 1991. "Steel Framing Replacing the 2x4 Stud". *San Francisco Chronicle*, April 24, 1991, Briefing section, p.10.

Jones, David A. 1990. "Windows of Opportunity". *Builder*. May 1990. p. 216.

Judkoff, Ron. 1991. "Mobile Home Retrofits Revisited: CMFERT Phase II". *Home Energy*. p. 21.

Judkoff, Ron, Rob DeSoto and Ed Hancock. 1990. "CMFERT: Training and Testing of Mobile Home Retrofits". *Home Energy*. p. 23.

Kahn, Cub. 1991. "Passive Solar Design: Housewarming with Many Efficient Returns". *Home Energy*. May/June 1991. p. 15.

Kahn, Edward. 1988. *Electric Utility Planning and Regulation*. Washington, DC: American Council for an Energy-Efficient Economy.

Kolb, J. O. and D. Baylon. 1989. *Evaluation of Infiltration in Residential Units Constructed to Model Conservation Standards*. Oak Ridge National Laboratory. ORNL/CON-257. March 1989.

Koomey, Jonathan. 1990a. *Comparative Analysis of Monetary Estimates of External Environmental Costs Associated with Combustion of Fossil Fuels*. Lawrence Berkeley Laboratory. LBL-28313. April 1990.

Koomey, Jonathan. 1990b. *Energy Efficiency Choices in New Office Buildings: An Investigation of Market Failures and Corrective Policies*. PhD Thesis, Energy and Resources Group, University of California, Berkeley.

Koomey, Jonathan, James McMahon and Cheryl Wodley. 1991. *Improving the Thermal Integrity of New Single-Family Detached Residential Buildings: A Regional Assessment of Capital Costs and Energy Savings*. Lawrence Berkeley Laboratory. LBL-29416. July1991.

Koomey, Jonathan, Arthur H. Rosenfeld and Ashok K. Gadgil. 1990. "Conservation Screening Curves to Compare Efficiency Investments to Power Plants." *Energy Policy*. vol. 18, no. 8. p. 774.

Krause, Florentin, John F. Busch and Jonathan G. Koomey. 1991. *Incorporating Global Warming Risks in Power Sector Planning: A Case Study of the New England Region*. Lawrence Berkeley Laboratory. LBL-31019. August 1991.

Krause, Florentin and Joseph Eto. 1988. *Least-Cost Utility Planning: A Handbook for Public Utility Commissioners (v.2): The Demand Side: Conceptual and Methodological Issues*. National Association of Regulatory Utility Commissioners, Washington, DC. December 1988.

Krause, Florentin, Arthur H. Rosenfeld, Mark D. Levine and et al. 1987. *Analysis of Michigan's Demand-Side Electric Resources in the Residential Sector (Prepared for the Michigan Electricity Options Study)*. Lawrence Berkeley Laboratory. LBL-23025. May 1987.

Krause, Florentin, Ed Vine and Sunita Gandhi. 1989. *Program Experience and its Regulatory Implications: A Case Study of Utility Lighting Efficiency Programs*. Lawrence Berkeley Laboratory. LBL-28268. October 1989.

LBL. 1990. *Appliance Energy Conservation Database*. Lawrence Berkeley Laboratory. September 1990.

LBL REM. 1991. *LBL's Residential Energy Model, which includes a database of elasticities, saturations, unit energy consumptions, conservation measures, capital costs, and other parameters*. Some of this information is contained in US DOE 1989b and McMahon 1986.

Lee, Allen. 1991. *Personal Communication:* "Estimates of infiltration rates of pacific northwest houses". Battelle, Pacific Northwest Laboratory. April 1991.

Lerman, David I. 1988. *Regional Study of Residential Water Heating Equipment: Phase II, Final Report*. ERC International, Portland, OR. ERC/PO-29--Prepared for Bonneville Power Administration and Pacific Power and Light. May 1988.

Lovins, A. B. 1987. *Advanced Electricity Saving Technologies and the South Texas Project*. Report to the City of Austin's Electric Utility Department. Pursuant to Contract #86-S300-FW. May 26,1987.

Lubliner, Michael and Marvin Young. 1990. "Is it All a Lot of Hot Air?--Mechanical Ventilator Performance". *Home Energy*. p. 25.

McMahon, James E. 1986. *The LBL Residential Energy Model*. Lawrence Berkeley Laboratory. LBL-18622. January 1986.

Meier, Alan. 1982. *Supply Curves of Conserved Energy*. PhD Thesis, Energy and Resources Group, University of California, Berkeley.

Meier, Alan. 1991. "Strategic Landscaping and Air Conditioning Savings: A Literature Review." *Energy and Buildings*. vol. 15, p. 479.

Meier, Alan, Jan Wright and Arthur H. Rosenfeld. 1983. *Supplying Energy Through Greater Efficiency*. Berkeley, CA: University of California Press.

MHI. 1989. *Summary of Manufactured Housing by States*. Manufactured Housing Institute.

MHI. 1990. *Life of Manufactured Homes: An Update*. Manufactured Housing Institute. August 1990.

MHI. 1991a. *HUD-Code Manufactured Homes: Popular ECO Packages, from the MHI Survey of Retailers*. Manufactured Housing Institute. January 1991.

MHI. 1991b. *Quick Facts About the Manufactured Housing Industry 1990/91*. Manufactured Housing Institute.

Miller, Peter M., Joseph H. Eto and Howard S. Geller. 1989. *The Potential for Electricity Conservation in New York State*. New York State Energy Research and Development Authority. September 1989.

Mills, Evan. 1984. "Raising the Energy Efficiency of Manufactured Housing." In *Proceedings of the 1984 ACEEE Summer Study on Energy Efficiency in Buildings*. Asilomar, CA: American Council for an Energy Efficient Economy.

Modera, Mark. 1991. *Personal Communication:* "Latest duct leakage information". Lawrence Berkeley Laboratory. February-April 1991.

Modera, Mark P. 1986. *Final Report: Residential Air Leakage Database Compilation*. Lawrence Berkeley Laboratory. LBL-23740. October 1986.

Moore, Bill. 1987. "Smart Windows". *Popular Science*. December 1987. p. 68.

Nadel, Steven. 1990. *Lessons Learned: A Review of Utility Experience with Conservation and Load Management Programs for Commercial and Industrial Customers*. New York State Energy Research and Development Authority. March 1990.

NEEPC, New England Energy Policy Council. 1987. *Power to Spare: A Plan for Increasing New England's Competitiveness Through Energy Efficiency*. Boston, MA. July 1987.

NPPC. 1986. *Northwest Conservation and Electric Power Plan*. Northwest Power Planning Council. Volumes 1 and 2.

NPPC. 1989. *Technical Appendix to Conservation Supply for the 1990 Power Plan*. Northwest Power Planning Council. 89-47A. November 21, 1989.

Orens, Ren. 1989. *Area-Specific Marginal Costing for Electric Utilities: A Case Study of Transmission and Distribution Costs*. Thesis, Department of Civil Engineering, Stanford University.

Ottinger, Richard L., David R. Wooley, Nicholas A. Robinson, David R. Hodas, Susan E. Babb, Shepard C. Buchanan, Paul L. Chernick, Emily Caverhill, Alan Krupnick, Winston Harrington, Seri Radin and Uwe Fritsche. 1990. *Environmental Costs of Electricity*. New York, NY: Oceana Publications, Inc., for the Pace University Center for Environmental and Legal Studies.

Perlman, Maier. 1987. "Residential Water Heating: Low-Tech and High-Tech Alternatives". *Energy Auditor and Retrofitter*. January/February 1987. p. 25.

Petrie, Beth and H. Gil Peach. 1988. *Residential Electric Water Heaters Dollar/Energy Savings, and Initial Price: Efficient vs. 1990 Standard Models Based on Data in the May 1988 Bonneville/Pacific Survey*. Pacific Power & Light. Prepared for Pacific Power & Light and the Regional Research Advisory Group for Appliance Efficiency,. August 8, 1988.

Pop Sci. 1989. "Windows Intended to Leak". *Popular Science*. December 1989. p. 38.

Rainer, Leo, Steve Greenberg and Alan Meier. 1990. "The Miscellaneous Electrical Energy Use in Homes." In *Proceedings of the 1990 ACEEE Summer Study on Energy Efficiency in Buildings*. Asilomar, CA: American Council for an Energy Efficient Economy.

RCG/Hagler Bailly Inc. 1990. *Electric and Gas Utility Modelling Systems: Technical Documentation*. Prepared for Office of Policy, Planning and Evaluation, EPA. DRAFT. December 21, 1990.

Real Goods. 1990. *Alternative Energy Sourcebook 1990*. Real Goods Trading Company, Ukiah, CA.

Ritschard, R. L. and Y. J. Huang. 1989. *Multifamily Heating and Cooling Requirements: Assumptions, Methods, and Summary Results*. Gas Research Institute. GRI-88/0239. November.

Schipper, Lee, Stephen Meyers and Henry Kelly. 1985. *Coming in from the Cold: Energy-Wise Housing in Sweden*. Washington, DC: Seven Locks Press.

Schlegel, Jeff. 1990. "Blower Door Guidelines for Cost-Effective Air Sealing". *Home Energy*. March/April 1990. p. 34.

Selkowitz, S. E. and C. M. Lampert. 1989. *Application of Large-Area Chromogenics to Architectural Glazings*. Lawrence Berkeley Laboratory. LBL-28012. June 1989.

SERI, Solar Energy Research Institute. 1981. *A New Prosperity: The SERI Solar/Conservation Study*. Andover, MA: Brick House Press.

Sherman, M. H., D. J. Wilson and D. E. Kiel. 1984. *Variability in Residential Air Leakage*. Lawrence Berkeley Laboratory. LBL-17587. April 1984.

Shuford, David. 1991. *Personal Communication:* "Discussion with Celina Atkinson of costs, energy savings, and production possibilities for heat pump water heaters". *Crispaire* in Atlanta, Georgia. 13 June 1991.

Sullivan, Robert. 1991. *Draft: RESFEN 1.0: A Prototype PC Program for Calculating Residential Fenestration Heating and Cooling Energy Use and Cost*. Windows and Daylighting Group, Lawrence Berkeley Laboratory. January 1991.

Turiel, Isaac, William J. Fisk and Mark Seedall. 1983. "Energy Savings and Cost-Effectiveness of Heat Exchanger Use as an Indoor Air Quality Mitigation Measure in the BPA Weatherization Program." *Energy*. vol. 8, no. 5. p. 323.

US DOE, U.S. Department of Energy. 1984. *Residential Energy Consumption Survey: Housing Characteristics 1984*. EIA, Energy Information Administration. DOE/EIA-0314(84).

US DOE, U.S. Department of Energy. 1988. *Technical Support Document: Energy Conservation Standards for Consumer Products: Refrigerators, Furnaces, and*

Television Sets. U.S. Department of Energy, Assistant Secretary, Conservation and Renewable Energy, Building Equipment Division. DOE/CE-0239. November 1988.

US DOE, U.S. Department of Energy. 1989a. *Residential Energy Consumption Survey: Housing Characteristics 1987*. EIA, Energy Information Administration. DOE/EIA-0314(87). May 1989 (also referenced as RECS 87).

US DOE, U.S. Department of Energy. 1989b. *Technical Support Document: Energy Conservation Standards for Consumer Products: Refrigerators and Furnaces*. U.S. Department of Energy, Assistant Secretary, Conservation and Renewable Energy, Building Equipment Division. DOE/CE-0277. November 1989.

US DOE, U.S. Department of Energy. 1990a. *Annual Energy Outlook: Long-Term Projections 1990*. Energy Information Administration. DOE/EIA-0383(90). January 1990.

US DOE, U.S. Department of Energy. 1990b. *Technical Support Document: Energy Conservation Standards for Consumer Products: Dishwashers, Clothes Washers, and Clothes Dryers*. U.S. Department of Energy, Assistant Secretary, Conservation and Renewable Energy, Building Equipment Division. DOE/CE-0299P. December 1990.

US DOE, U.S. Department of Energy. 1991. *Annual Energy Outlook, with Projections to 2010*. Energy Information Administration. DOE/EIA-0383(91). March 1991.

Usibelli, Anthony, Betsy Gardiner, W. Luhrsen and Alan Meier. 1983. *A Residential Conservation Database for the Pacific Northwest*. Lawrence Berkeley Laboratory. LBL-17055. November 1983.

Warner, Jeffrey L. 1990. "Consumer Guide to Energy-Saving Windows". *Home Energy*. July/August 1990. p. 17.

XENERGY. 1990. *An Assessment of the Potential for Electrical Energy-Efficiency Improvements in the SMUD Service Territory*. Prepared for the Sacramento Municipal Utility District. Vol I: Results and Methods; Vol II: Technical Appendix. July 9, 1990.